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Determination of Pomological Characters and Phenolic Compounds of Cornelian Cherry Genotypes

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ABSTRACT

Cornelian cherry is a fruit noted for its attractive appearance, unique flavor, and rich phenolic content. This study aimed to understand the effects of genotypic differences and altitude on fruit quality by thoroughly examining the pomological and phenolic characteristics of cornelian cherry genotypes selected at different altitudes using principal component analysis (PCA) and heat map methods. The high-altitude G2 genotype stood out with the highest fruit weight and soluble solids content. While catechin was the dominant phenolic compound in all genotypes, genotypes G1 and G2 stood out with their high levels of gallic and syringic acid. PCA and heat map analyses clearly showed that the high-altitude G1 and G2 clustered together with similar traits. At the same time, the low-altitude G4 exhibited distinct profiles focused on high acidity and pit width, and G3 on fruit and pit sizes and various phenolics. These findings highlight the diversity and breeding potential of cranberry genotypes and also reveal that altitude is a factor determining pomological properties and phenolic compound content.

Keywords: *Cornus mas*; Bioactive compounds; altitude; PCA; heatmap cluster.

INTRODUCTION

Cornelian cherry (*Cornus mas* L.) is one of the fruit species known in Turkey and the world, but has few commercial orchards. Anatolia, the Balkans, the Caucasus, the Mediterranean Basin, Asia, and Europe are among the origin countries of cornelian cherry (Balta *et al.,* 2020). Cornelian cherry has many natural habitats in Iran, Azerbaijan, Georgia, Türkiye, and Serbia (Szot *et al.*, 2023). There are 65 species of cornelian cherry, and the economically cultivated species is *C. mas* L. Most of the other species are grown as decorative plants (Demir *et al.*, 2020). Cornelian cherry genotypes occur naturally as single shrubs or in several tree forms in mountainous and forested areas and near river valleys (Güleryüz *et al.*, 1998); these plants can live for up to 300 years and are resistant to drought and frost (Bayram and Ozturkcan, 2020).

Its fruits are sour,juicy, and rich in vitamin C. It is known by the names Kiren, Güren, and Zuhal. Stems, bark, and fruits are utilized (Karadeniz, 2004). Cornelian cherries are rich in

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anthocyanins, which are known to improve blood values and reduce the risk of cardiovascular and metabolic diseases (Szot *et al.*, 2024). It has been used for many years in the treatment and prevention of diarrhea, sore throat, digestive disorders, varicella, anemia, rickets, and liver and kidney diseases (Kaya and Koca, 2021).

Phenolic compounds, which are secondary metabolites that play a role in defense against biotic and abiotic stress in plants, are responsible for various properties, such as flavor, smell, and color, and are essential for human health (Kutlu et *al.*, 2021). Cornelian cherry fruits are rich in chemoprotective substances such as flavonoids, phenolic acids, terpenes, carotenoids, vitamins, and organic acids (Lidiková *et al.*, 2024). Therefore, it is considered a superfood (Bayram and Ozturkcan, 2020).

Genetic diversity has emerged as cornelian cherries have been propagated from seeds for centuries (Balta et al., 2020). Therefore, there is a rich cornelian cherry population in Türkiye (Karadeniz, 2019). There are differences in fruit characteristics within this rich population (Demir *et al.*, 2020). To reveal these differences, selection breeding studies should be used to scan and examine the existing population and evaluate the genotypes that stand out in terms of fruit characteristics, protect them, and bring them into production (Ünver, 2023).

Cornelian cherry are among the fruits that have become popular in recent years. The consumption of fruit as food and its effects on human health increase its cultivation. Among cultivated cornelian cherries, the demand for products with more attractive colors, larger fruits, and smaller seeds is increasing (Kazimierski *et al.*, 2019). Morphological features facilitate rapid and simple evaluation and have been used to assess genetic diversity among morphologically distinguishable specimens. The data obtained by combining morphological features with nickel and quantitative features are used in multivariate analyses to reveal essential details in evaluation and classification (Mratinić *et al.*, 2015). Kalalagh *et al.* (2016) reported that there is diversity among cornelian cherry genotypes using data analyses such as descriptive statistics and clustering. Cornelian cherries exhibit high variability in their bioactive content, and this variability varies according to biotic and abiotic factors such as genotype, environmental conditions, harvest time, and storage conditions. Specific genetic and phytochemical analyses of the genotypes to be selected and evaluation of polymorphisms between genotypes are essential for future selection studies (De Biaggi *et al.*, 2018).

Climate factors vary depending on changes in altitude (Aslantaş and Karakurt, 2007). Differences in factors such as humidity and temperature depend on altitude and change the morphological and anatomical characteristics of plants (Gülsoy *et al.*, 2019). For this reason,

cornelian cherry fruits with genetic diversity need to adapt to environmental conditions at different locations (Cornescu Frătuțu and Cosmulescu, 2019).

The origin of cornelian cherry genotypes/varieties has a significant impact on fruits (Zuzana *et al.*, 2021). Cornelian cherry fruits are among the most important fruits in our country's fruit folklore (Karadeniz, 2004). According to the 2023 data of the Türkiye Statistical Institute, 12 thousand 167 tons of cornelian cherry were grown in the area of 1856 da in Türkiye. In Türkiye, cornelian cherry are grown in 38 provinces, especially Kastamonu (3982 tons), Samsun (1125 tons), Bartın (828 tons), and Sinop (474 tons). Bolu Province ranks 9th in Turkey in terms of cornelian cherry production, with 392 tons (TÜİK, 2024). Plant genetic resources are essential for plant breeding to evaluate the beneficial traits of genetic resources and to combine these traits in a single variety. To achieve this, it is crucial to identify genetic resources and reveal their superior characteristics. In this context, the identification through selection of cornelian cherry fruits, which can survive naturally even in mountainous and forested areas at an altitude of 1400 meters (Bayram and Öztürkcan, 2020), is crucial because cornelian cherry fruits are among Türkiye's genetic resources. This large genetic population, comprehensive and systematic studies on how cornelian cherry genotypes depend on the altitude at which they grow are limited. While the existing literature focuses on general characteristics of cornelian cherry, insufficient information is available to provide detailed comparative analyses of genotypes collected from different altitudes. This research aims to determine the pomological characteristics and phenolic compound contents of cornelian cherry selected from various altitudes and to reveal their relationships.

MATERIALS AND METHODS

Plant materials and weather conditions

The plant material consists of productive, large-fruited, and attractive cornelian cherry genotypes found in the Seben (Korucuk) and Merkez (Merkeşler) districts of Bolu. Genotypes from the Korucuk/Seben region are located at altitudes of 1182 m (G1) and 1172 m (G2), while those from the Merkeşler/Merkez neighborhood are located at altitudes of 776 m (G3) and 665 m (G4). The genotypes are located away from residential areas, in forested areas, or along stream banks. In 2019 and 2020, 500 grams of fruit from each genotype were collected to represent the tree. Fruits from the different genotypes were stored in a +4°C refrigerator until pomological analyses were performed. To determine phenolic compounds, fruit samples of the genotypes were juiced, placed in Falcon tubes, and stored at -20°C until analysis. Long-term monthly mean temperature ranged from 7.08°C to 20.75°C in the Central district (April-

November), and from 7.19°C to 22.47°C in the Seben district. April, June, and October receive more precipitation than the other months of the season in the region. Average relative humidity is similar to monthly rainfall in terms of monthly distribution, ranging from 72.32% (May) to 75.58% (October) in the Central district and from 66.39% (October) to 68.66% (June) in the Seben district. Figure 1 shows the long-term climate data of the region.

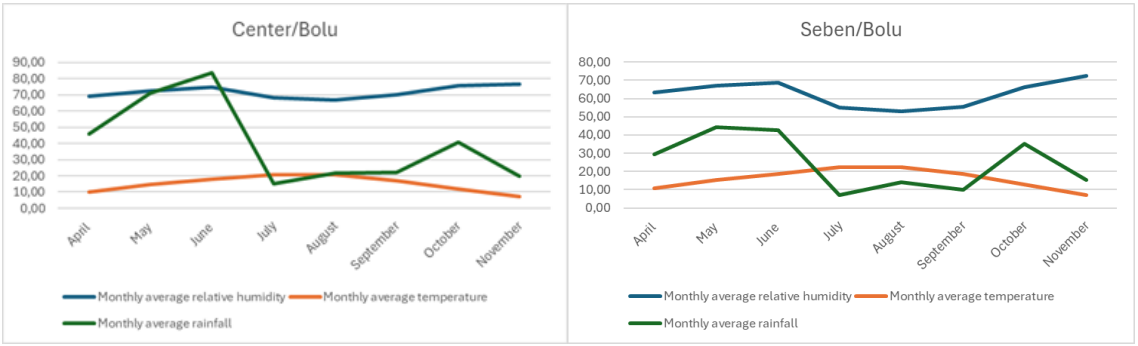

Figure 1. Average climate data of the central and Seben districts between 2011-2021.

In 2020, monthly temperatures were almost identical to the long-term distributions with very little deviation. There was a 2°C increase in September and October in the central district and a 3°C increase in Seben district. In both districts, the precipitation regime was significantly lower than the long-term trend, except for June, with no precipitation in August. This is shown in **Figure 2**.

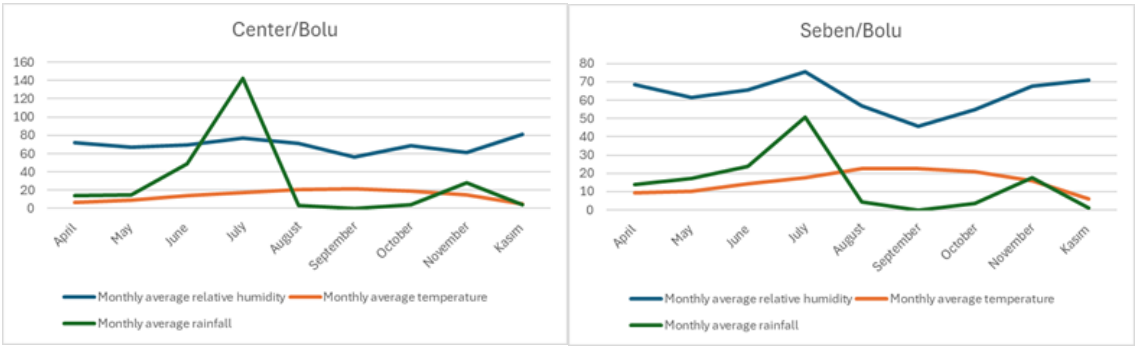

Figure 2. The climate data of Merkez and Seben in 2020.

Pomological analyses

All measurements for each genotype were performed on 20 randomly selected fruits. Fruit (FW) and stone (CW) weights were determined using a digital scale with a precision of 0.01 g (Karadeniz, 1995). Fruit length (FL), fruit width (FWW), core length (CL), and core width (CWW) were measured with a digital caliper to a precision of 0.01 mm. The fruit and core shape indices (FSI-CSI) were obtained by dividing the fruit and core width by the fruit and core length. (Güneş, 1997). Fruit flavor (FT) was rated on a scale of 1 to 4 by five different

individuals (Güleryüz, 1988).The water-soluble solids content (SSC) of the fruits was determined via a hand refractometer (Greinorm, Germany) The pH and titratable acidity (TA) were measured with a bench pH meter (Hanna HI9124, Romania). The amount of sodium hydroxide required for the TA was determined, and the acidity was calculated in terms of % malic acid.

The L*, a*, b*, chroma, and hue values of the fruits were measured on two different surfaces with a colorimeter (Konica Minolta Sensing, Inc., Osaka, Japan).

Phenolic compound analysis

Phenolic compound concentrations were determined according to the modified method of Pehluvan *et al.* (2015). For the extraction of phenolic compounds, 10 ml of solvent (50% water: 50% acetonitrile) was added to 5 g of fruit sample from each genotype, and the mixture was crushed in a homogenizer and centrifuged at 15 000 rpm for 15 minutes.

Chlorogenic acid (LGC-Dr. Ehrenstorfer Standards GmbH C 11415750), caffeic acid (LGC-Dr. Ehrenstorfer Standards GmbH C 10934700), rutin hydrate (Sigma R5143-50G), q-coumaric acid (Aldrich H22809-5G), myricetin (Sigma 70050-25 mg), *p*-coumaric acid (Fluka 55823-50 mg), syringic acid (Chem Service NG-17689-1G), gallic acid (Chem Service N-12105-2G), quercetin (Chem Service NG-BS100- 1G), and catechin (Fluka 43412-10 mg) standards were used.

Phenolic extracts were analyzed via Shimadzu CTO-20A HPLC. A DGU-20A5 degaser system, an LC-20AT model pump, and an SPD-M20A model diode array detector (DAD) were used. An Inertsil ODS-3V (5 µm, 4.6 × 250 mm) column was used. The injection volume was determined to be 20 µL (microliter). Peaks were detected between 273 and 370 nm in wavelength. The holding times of the standards were determined, and the readings were made with subsequent calibration.

Statistical analysis

Analysis of variance (ANOVA) was applied to identify significant differences among the traits examined in cranberry genotypes. Principal component analysis (PCA) and hierarchical cluster analysis (JMP Pro 17) were performed to assess the relationships between the characteristics examined and the genotypes.

RESULTS AND DISCUSSION

The Pomological characteristics of the cornelian cherry fruits are given in **Table 1**. In the research, FW varied between 2.36 g (G4)-3.13 g (G2) and CW 0.41 g (G1)-0.49 g (G3)

among the genotypes. In terms of FL, G4 (18.36 mm) had the shortest fruit length, while G3 (23.17 mm) had the most extended fruit length. The highest core length was determined to be in G3, at 17.53 mm. While the most significant fruit widths are in G2, the largest core widths are in G4. The most significant values of the shape index were in G4 for both the fruit and the core. The best fruit tastes were in G3. Taş *et al.* (2023) reported a weight between 1.44 and 3.40 g; Skender *et al.* (2022), 1.38 and 3.01 g; Güzel (2021), 1.27 and 2.53 g; Borroto Fernández *et al.* (2022), 1.38 and 2.58 g; and Cosmulescu and Cornescu (2020), reported a weight between 1 and 2.67 g. Other researchers reported core weights of 0.59 g (Kalkan *et al.*, 2023), 0.22-0.58 g (Cosmulescu and Cornescu ,2020), 0.171-0.436 g (Borroto Fernández *et al.*, 2022), and 0.20-1.13 g (Taş *et al.*, 2023). Our fruit weight and core weight data are consistent with previous studies. Fruit weight is one of the important selection criteria. Fruit weights were taken into consideration for the selected fruits. Considering the altitude, fruit weights are greater at higher altitudes, and as the altitude decreases, fruit weights decrease. In fact, in a study conducted at altitudes of 345, 389, and 700 m, the largest fruits were detected at high altitudes in the first year, and similar results were obtained in the second year at an altitude of 389 m (Drkenda *et al.*, 2014). Therefore, the year factor may be an effective factor influencing fruit weight (Drkenda *et al.*, 2014). Again, in a study examining cornelian cherry from different regions, the fruit weights were 0.94-1.92 g at 513 m altitude, 0.86-2.53 g at 680 m altitude, 0.82-1.86 g at 744 m altitude, and 1.19 g at 1162 m altitude. It has been reported that it varies between 0.74 and 2.94 g at an altitude of 2.97 g and 1723 m (Mratinić *et al.*, 2015). Examining altitude, Mratinić *et al.* (2015) found that our fruit weight values yielded more accurate results. In a study conducted at an altitude of 1032-1069 m, fruit weights were reported to be 0.78-1.72 g (Okatan, 2016). According to the researcher's findings, fruit weights at high altitudes reach their maximum values at an altitude of 1162 m. Again, in a study conducted at an altitude of 1400 m, fruit weights were reported to vary between 0.5 and 3.4 g (Brindza *et al.*, 2006). In a study conducted at 820 and 1200 m in altitude, fruit weights were reported to vary between 1.74 and 2.57 g and between 1.90 and 2.02 g, respectively. According to the results of this research, our data on fruit weights yielded greater results (Islamovic *et al.*, 2014). Since fruit weight and attractiveness are the most important parameters in consumer preferences, the genotypes we chose are important for future breeding studies because they grow under natural conditions without applying cultural processes.

Table 1. Fruit and core characteristics of cornelian cherry genotypes.

Genotypes	FW (g)	FL (mm)	FWW (mm)	CW (g)	CL (mm)	CWW (mm)	FSI	CSI	FT
G1	2.69± 0.18b	20.62± 0.66b	14.78± 0.81a	0.41± 0.06b	15.14± 0.61b	6.16± 0.36c	0.72± 0.05b	0.41± 0.03c	1.33± 0.58c
G2	3.13± 0.16a	21.04± 0.66b	15.20± 0.60a	0.45± 0.06ab	15.24± 0.66b	6.66± 0.34ab	0.73± 0.02ab	0.44± 0.02b	3.33± 0.58ab
G3	2.62± 0.12b	23.17± 0.70a	13.91± 0.46b	0.49± 0.04a	17.53± 0.63a	6.36± 0.22bc	0.57± 0.03c	0.36± 0.02d	4.00± 1.00a
G4	2.36± 0.21c	18.36± 0.62c	13.30± 0.67c	0.42± 0.04b	13.79± 0.26c	6.78± 0.30a	0.76± 0.05a	0.49± 0.02a	2.33± 0.58bc

*Different letters in the same column indicate significant differences at $p \leq 0.05$.

The SSC, pH, and TA properties of the examined genotypes are given in **Table 2**. G2 is in the same group in terms of SSC and pH. The SSC ranged from 14.33% in G1 to 20.33% in G2, indicating significant genotypic variation. Other researchers have reported SSC values of 8.90-16.83% (Bektaş and Koyuncu, 2023), 8-13% (Karadeniz, 2019), 14.5-20.0% (Karadeniz *et al.*, 2009), 9.8-13.6% (Balta *et al.*, 2020), 10.37-21.22% (Taş *et al.*, 2023), 12.50-21.00% (Tural and Koca, 2008), and 8.75- 18.66% (Kalkan *et al.*, 2023). In general, the amount of sugar and acid in fruits increases due to ripening at high temperatures and under light conditions (Aslantaş and Karakurt, 2007). In our study, the SSC value of the G1 genotype found at high altitudes matches the literature values. The unexpectedly low SSC value in G1, despite its high altitude, may be attributed to delayed maturation or local microenvironmental factors such as shading, although these conditions were not directly measured in this study.In a study conducted at an altitude of 960 m, the SSC varied between 11.13 and 16.5% (Gunduz *et al.*, 2013). Additionally, in a study conducted at 850 and 1200 m altitudes, Islamovic *et al.* (2014) reported that the SSC values were between 16.95 and 21.1% and 18.21 and 20.9%, respectively. Okatan (2016) reported that in his study of 9 genotypes between 1032 and 1069 m in altitude, the SSC values were between 11.8 and 17.2%. According to the findings of the researchers, our SSC values gave better results. Similarly, in a study conducted at different altitudes, Mratinić *et al.* (2015) reported SSC values ranging from 14.8-30.8% at 513 m, 15.8-26.8% at 680 m, 14.3-27.0% at 744 m, 15.3-24.6% at 1162 m and 13.8-21.5% at 1723 m. Additionally, the highest SSC values were recorded for the 513 m altitude. According to the researcher's findings, although our SSC values are generally similar, our results are lower than the value at 513 m, where it reaches its maximum value. The wide variation in SSC content results may not be solely dependent on genotype and maturity stage. It can vary depending on environmental factors and geographical regions (Cosmulescu and Cornescu, 2020), as well as on growing conditions (Karadeniz, 2019). However, Gunduz et al. (2013)

reported that SSC values differed between reddish cranberries and more mature, dark red cornelian cherry. This supports our data.

In this research, the pH values vary between 2.98 (G4) and 4.02 (G2), and the acidity between 1.41% (G2) and 3.68% (G4). While the highest pH value was measured in the G2 genotype, TA gave this result in G4. Previously described pH and acidity values were reported as 2.85–3.23 and 0.91–2.92%, respectively (Skender *et al.*, 2022); 3.11–3.53 and 1.10–2.53%, respectively (Tural and Koca, 2008); 3.41 ─ 3.69 and 1.41─2.48%, respectively (Güzel, 2021); 2.44-3.45 and 1.01-2.46%, respectively (Taş *et al.*, 2023); and 2.96- 3.48 and 1.74%-3.82, respectively (Kalkan et al., 2023). In a study conducted at an altitude of 960m, the pH was between 2.7 and 3.0, and the acidity was between 2.0 and 3.00% (Gunduz *et al.*, 2013); at an altitude of 1032 and 1069 meters, the pH was reported to be between 2.60 and 4.02 (Okatan, 2016). While our results are consistent with those of other researchers, our data appear slightly higher. This may be due to specific environmental conditions and many factors such as harvest time, variety/genotype, and altitude, as reported by Yılmaz et al. (2009).

Table 2. SSC, pH and TA characteristics of cornelian cherry genotypes.

Genotypes	SSC (%)	pH	TA (%)
G1	14.33±0.58c	3.15±0.01c	3.01±0.01b
G2	20.33±0.58a	4.02±0.03a	1.41±0.01c
G3	18.00±1.00b	3.34±0.03b	1.47±0.13c
G4	18.33±0.58b	2.98±0.08d	3.68±0.08a

*Different letters in the same column indicate significant differences at p ≤0.05.

The color characteristics of the fruits of the cornelian cherry genotypes are given in **Table 3**. No significant difference was found between the genotypes in terms of L* values. According to the fruit color characteristics, the L* values were 27.20 (G2)-31.02 (G1), a* 15.11 (G3)-29.83 (G1), b* 3.19 (G3)-13.81 (G1), chroma 15.44 (G4)-33.09 (G1) and hue 11.89 (G3)-23.23 (G1). Tural and Koca (2008) reported L*10.82–19.69, a* 6.25–15.59, and b* 3.46–6.64 in Samsun ecology. The L*, a*, and b* values are reported as 25.18─33.00, 9.74─30.26, and 2.46─14.41, respectively (Güzel, 2021), and 25.91-36.80, 24.54-41.00, and 11.27-27.75, respectively (Bektaş and Koyuncu, 2023). TAŞ et al. (2023) reported that the color values changed between L* 26.99-33.00, a* 10.79-25.93, b* 5.62-19.46, chroma 12.11-29.08, and hue value 21.32-30.65. While the color measurements of our genotypes are not similar to those of Tural and Koca (2018), they are similar to those of other researchers. In our study, colorimetric measurements revealed a dominant a value and a wide range of b values across our genotypes. Therefore, unlike Tural and Koca (2008), our genotypes differ by

having a more reddish and vibrant hue. This is expected, as factors such as genotypic traits, environmental conditions, and harvest maturity can influence fruit color.

Table 3. Fruit color characteristics of cornelian cherry genotypes.

Genotypes	L*	a*	b*	Chroma	Hue
G1	31.02±5.07	29.83±7.32a	13.81±8.55a	33.09±10.27a	23.23±7.93a
G2	27.20±0.90	23.82±4.63ab	10.07±2.56ab	25.87±5.26ab	22.73±1.49a
G3	27.66±0.55	15.11±0.60b	3.19±0.42b	20.55±0.67b	11.89±1.12b
G4	28.70±0.89	19.75±6.03b	5.58±2.91ab	15.44±6.58b	14.95±3.89ab

*Different letters in the same column indicate significant differences at p≤ 0.05.

In this research, 10 phenolic compounds were identified: gallic, catechin, chlorogenic, caffeic, syringic, *p*-coumaric, rutin, *q*-coumaric, myricetin, and quercetin. In this study, the difference in phenolic compound levels according to genotype was found to be statistically significant (**Table 4**). Catechin was the dominant phenolic compound in all genotypes. G1 yielded the highest values for gallic acid, chlorogenic acid, and myricetin. G2 exhibited significantly higher concentrations. G2 had the highest phenolic content among the catechin and syringic acid samples. G3 exhibited higher levels. The G3 genotype appeared to yield higher values for caffeic acid, *p*-coumaric acid, rutin, *q*-coumaric acid, and quercetin. Taş and Gundogdu (2023) reported the following results: gallic acid 0.37-2.68 mg/100 g, catechin 4.00- 28.66 mg/100 g, caffeic acid 0.32-0.95 mg/100 g, syringic acid 0.25-1.62 mg/100 g, *p*-coumaric acid 0.53-5.12 mg/100 g, *q*-coumaric acid 1.03 -8.55 mg/100 g, rutin 0.31-1.17 mg/100 g, chlorogenic acid 4.54-17.98 mg/100 g and quercetin 0.25-3.04 mg/100 g. Researchers reported that ellagic acid, catechin, and chlorogenic acid contents were greater than those of other phenolic compounds. Cosmulescu *et al.* (2019) reported that gallic acid concentrations ranged from 5.29-37.17 mg/100 g, coumaric acid concentrations ranged from 0.42-41.87 mg/100 g, rutin concentrations ranged from 1.18-10.85 mg/100 g, and myricetin concentrations ranged from 19.80-32.33 mg/100 g; moreover, due to the high diversity limits of cornelian cherry, these compounds can be affected by genotypic and environmental factors. Lidiková *et al.* (2024) evaluated neochlorogenic compounds, chlorogenic compounds, caffeic acid, and rutin as phenolic compounds in genotypes and varieties collected in Ukraine. The researcher reported chlorogenic acid as 1.33–7.32 mg kg−1, caffeic acid as 1.33–6.02 mg kg−1, and rutin as 6.67–20.67 mg kg−1. Ozrenk *et al.* (2023) identified 8 phenolic compounds, including gallic acid, chlorogenic acid, *q*-coumaric acid, ferulic acid, *p*-coumaric acid, ellagic acid, caffeic acid and quercetin, in their study under Erzurum conditions. In the researchers' study, gallic acid (4.31-38.93 mg/100 g), chlorogenic acid (2.64-10.88 mg/100 g), *q*-coumaric acid (0.87-9.91 mg/100 g), *p*-coumaric acid (0.63-3.84 mg/100 g), caffeic acid (1.16-15.30 mg/100 g) and quercetin (0.66-6.39 mg/100 g) were determined. Martinović and

Cavoski (2020) reported in their study on cornelian cherry genotypes and local varieties that caftaric acid was the dominant phenolic acid, and quercetin and kaempferol derivatives were the dominant flavonoids. In their study, researchers reported that gallic acid concentrations ranged from 0.77-6.80 mg/100 g, cafeic acid concentrations ranged from 0.58-3.97 mg/100 g, and chlorogenic acid concentrations ranged from 0.32-6.40 mg/100 g. Szczepaniak *et al.* (2021) reported that in their study on the effect of color on phytocompounds, the dominant compounds were chlorogenic acid, gallic acid, quercetin, rutin, and naringenin. In their studies at 400 and 900 m, Bajić-Ljubičić *et al.* (2018) reported that the amounts of phenolic compounds were related to altitude. They detected more chlorogenic acid in fruits at 700 m in altitude than at 345 and 389 m in altitude (Drkenda *et al.*, 2014). While some of our phenolic compound findings overlap with those of other researchers, some differences are evident. The synthesis and accumulation of bioactive compounds are regulated by specific chemical processes within plant cells. Genetic variation among cornelian cherry genotypes can influence the functioning of these processes, leading to significant changes in the types and amounts of compounds (Lidiková et al., 2024). This suggests that the phenolic compound content and quantity of cornelian cherry fruits can vary depending on various environmental conditions (Bajić-Ljubicić et al., 2018) and that genetic differences exist among genotypes and cultivars (De Biaggi et al., 2018). Therefore, the main reason for the discrepancies between our findings and those of other researchers is that the plant's genetic makeup and growing environment differentially influence the ways it produces these beneficial compounds.

Table 4. Gallic acid, catechin, chlorogenic acid, caffeic acid, syringic acid, *P*-coumaric acid, rutin, *Q*-coumaric acid, myricetin, and quercetin acid contents of the fruits of cornelian cherry genotypes (mg kg^{-1}).

Genotypes	Gallic	Catechin	Chlorogenic	Caffeic	Syringic	*P*-coumaric	Rutin	*Q*-coumaric	Myricetin	Quercetin
G1	6.77± 0.01a	7.90± 0.07b	0.63± 0.01a	0.85± 0.01c	2.25± 0.12b	0.40± 0.07b	0.88± 0.08b	0.21± 0.02c	0.92± 0.02a	0.63± 0.02ab
G2	6.56± 0.04ab	28.60± 0.64a	0.43± 0.05b	0.41± 0.01d	2.94± 0.22a	0.52± 0.01b	0.80± 0.02b	0.28± 0.04bc	0.25± 0.01c	0.71± 0.03a
G3	4.82± 0.56b	9.12± 0.91b	0.43± 0.01b	1.52± 0.07a	1.84± 0.04b	2.65± 0.56a	4.65± 0.75a	1.63± 0.08a	0.54± 0.04b	0.73± 0.04a
G4	2.97± 1.81c	4.05± 2.10c	0.30± 0.18b	1.25± 0.01b	1.06± 0.55c	0.30± 0.20b	0.58± 0.31b	0.71± 0.45b	0.44± 0.25bc	0.44± 0.25b

*Different letters in the same column indicate significant differences at $p \leq 0.05$.

Principal Component Analysis (PCA) was employed to demonstrate the relationships between cornelian cherry genotypes and fruit traits (Figure 3). Principal Component 1 (PC1) explained 33.1% of the total variance, and Principal Component 2 (PC2) explained 27.8%, resulting in a cumulative variance of 60.9% for both components. PCA revealed distinct clustering patterns among the genotypes.The most notable finding from the PCA was the clear segregation of genotypes based on their geographical origin, particularly altitude. The G1 and

G2 genotypes, both originating from high-altitude regions, consistently clustered together on the same axis. This proximity indicates they share common underlying traits, suggesting a strong influence of high-altitude adaptation on their pomological and biochemical profiles. In particular, the G1 genotype exhibited dominance in color traits and myricetin content, indicating a strong influence of the genotype on visual appeal and a key flavonoid. The G2 genotype was notable for its fruit weight, pH, and significant syringic acid and catechin content, highlighting its potential for desirable physical and some phenolic traits. Their grouping underscores the potential for selecting high-yielding and phenolics-rich accessions specifically adapted to elevated environments. In contrast, the G3 and G4 genotypes, collected from distinct and generally lower-altitude regions, were located on different axes and separated from the high-altitude cluster, revealing their unique profiles. G3 was more pronounced in terms of fruit taste, rutin, and p-coumaric acid, indicating sensory quality and potential for specific phenolic acid richness. This distinct separation of G3 and G4 from G1 and G2, and each other, strongly suggests that altitudinal differences, possibly coupled with other environmental or localized genetic factors, play a significant role in shaping the unique trait combinations of these genotypes. A more in-depth examination of the PCA revealed complex relationships among phenolic compounds. Syringic acid, gallic acid, chlorogenic acid, and catechin exhibited positive correlations with each other, while caffeic acid showed a negative correlation. This suggests that these phenolic compounds are often found together or that their synthesis pathways interact, but caffeic acid metabolism may exhibit a different dynamic. All these results demonstrate that cornelian cherry genotypes exhibit significant diversity in terms of pomological and phenolic compound composition, with environmental factors like altitude being a key driver of this observed variation and clustering.

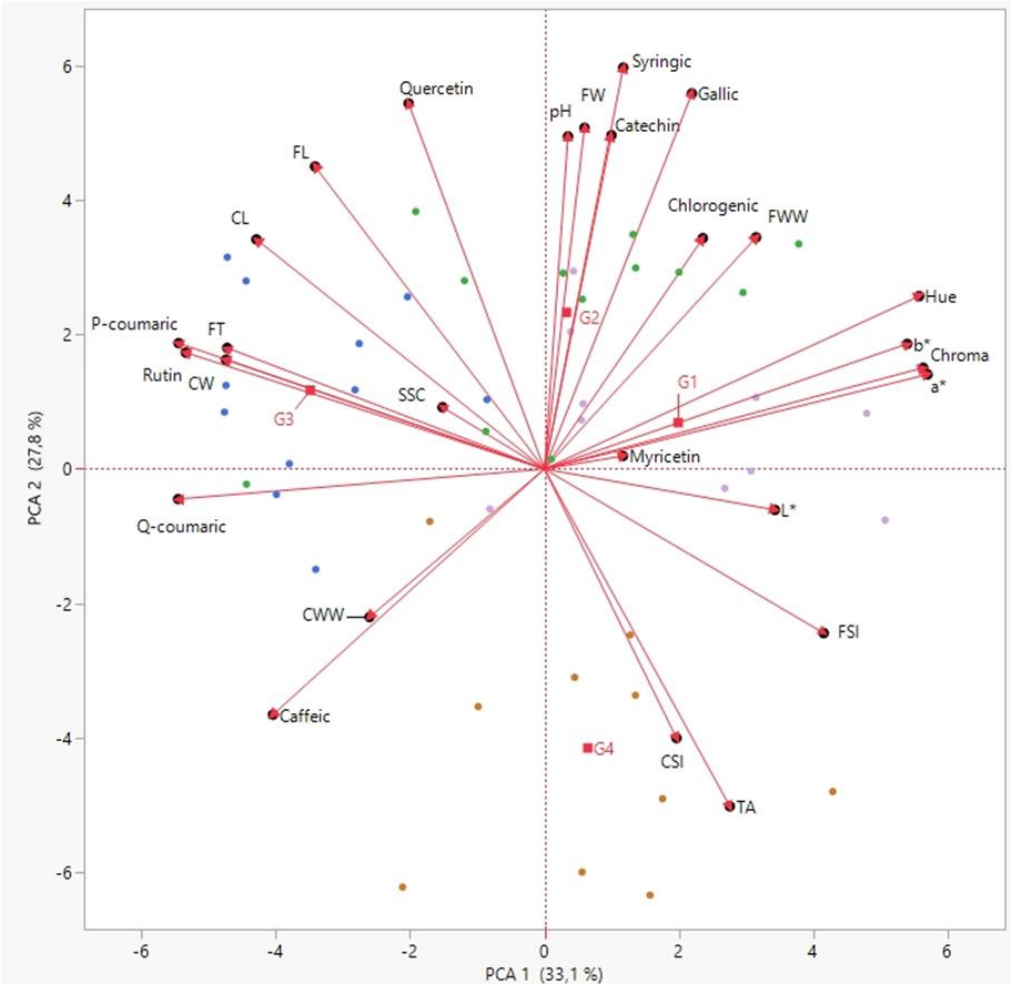

Figure 3. Principal component analysis (PCA) plot for cornelian cherry genotypes and examination characteristics.

The results of the heatmap hierarchical clustering analysis performed between the cornelian cherry genotypes and the examined characteristics are shown in **Figure 4**. The examined cornelian cherry genotypes were divided into two separate groups: A and B. The G1 and G2 genotypes were located in cluster B2, and the G4 genotype was located in cluster B1. Only the G3 genotype was included in cluster A. We examined 27 variables. These variables are divided into two main groups, X and Y, and two separate subclusters in each cluster: X1 and X2 and Y1 and Y2. There are 13 variables in the X1 subset: FW, syringic, pH, catechin, FWW, hue, a*, chroma, b*, gallic, chlorogenic, L*, and myricetin. There are 5 variables in cluster X2: CWW, SSC, TA, FSI and CSI. There are 5 variants in the Y1 subgenotype. These were FL, CL, quercetin, CW and FT. In Y2 subgroup, there are 4 variables: caffeic acid, *p*-coumaric acid, rutin, and *q*-coumaric acid. Heat map analysis revealed distinct phytochemical and quality profiles among cornelian cherry genotypes, influenced by altitude differences, indicating that each genotype holds significant breeding potential for specific applications. High-altitude G1 and G2 genotypes generally exhibited

values for fresh consumption and aesthetic characteristics. G1 intensified vibrant red coloration (hue, a*, chroma, b*, L*) and specific antioxidant phenolics (gallic acid, chlorogenic acid, myricetin). At the same time, G2 was distinguished by larger size (FW, FWW), balanced flavor (SSC, pH), and rich antioxidant content (syringic acid, catechin, quercetin). These findings suggest that high-altitude cultivars are generally preferred for visual quality and balanced flavor. In contrast, G3 and G4 genotypes from lower altitudes provided advantages in traits related to processing efficiency and yield. G4 demonstrated its suitability for processed products with high total acidity (TA), core width (CWW), and specific fruit and core shape indices (FSI, CSI). G3 demonstrated its potential in terms of productivity and bioactive diversity by offering long fruit and core sizes (FL, CL), high core weight (CW), and a wide range of phenolic compounds (quercetin, *p*-coumaric acid, rutin, *q*-coumaric acid, caffeic acid). Consequently, it has been observed how environmental factors such as genetic makeup and altitude shape the bioactive and quality traits of cornelian cherry. This provides a critical foundation for cornelian cherry breeding programs, enabling the development of new varieties targeted to meet specific market demands or health applications.

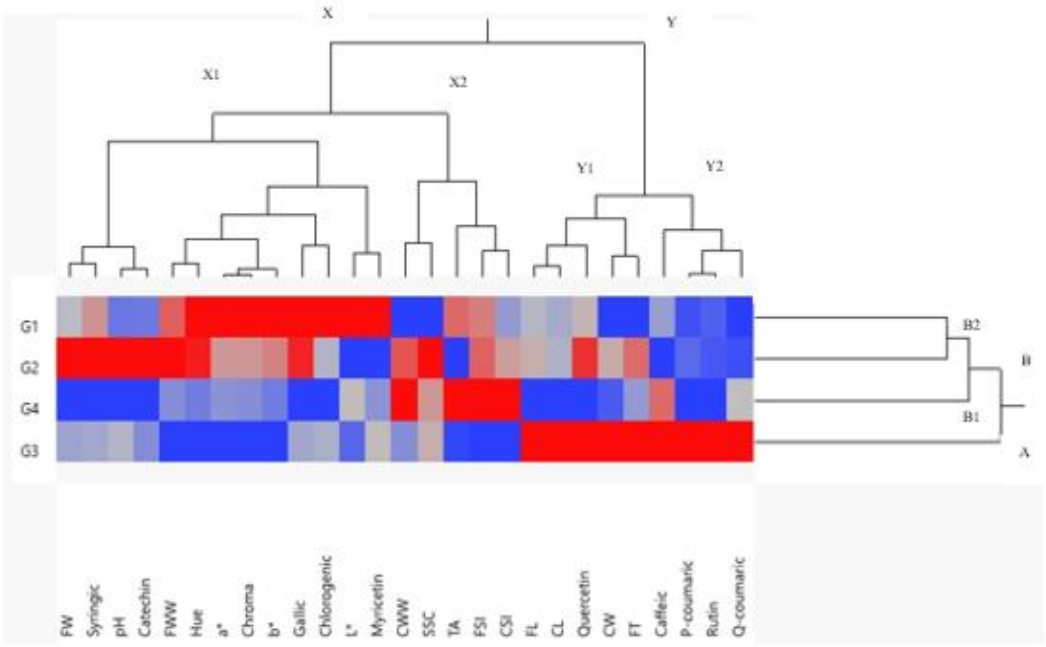

Figure 4. Heatmap obtained as a result of hierarchical clustering analysis of cornelian cherry genotypes and examination characteristics. On the temperature scale, colors shifting to red indicate an increase, and colors shifting to blue indicate a decrease.

CONCLUSIONS

Cornelian cherry fruits are known for their nutritional and bioactive phytochemical richness, and Türkiye hosts a large cornelian cherry region. This, combined with the significant

protective effect of provenance on fruit traits, increases the potential for the discovery and evaluation of new genotypes through breeding research. In this study, significant differences in fruit and phenolic moisture content were identified between genotypes from similar high altitudes (G1 and G2) and similar low altitudes (G3 and G4). Altitude significantly shaped fruit weight (FW), soluble solids content (SSC), and phenolic plant composition, but the genetic origin and cultivar characteristics of the genotype played a role in these changes. Indeed, while catechin was dominant in all genotypes, an effect of altitude on gallic acid and lovageic acid was observed. Principal Component Analysis (PCA) and heat map managerial clustering analysis reveal strong relationships among scatter, cornelian cherry genotypes, and traits and how they interact with altitude differences in this temperature range: high altitude G1 and G2 genotypes presented titratable acid and (TA), core width (CWW), furit and core length (FL, CL), core weight (CW) and wide physiological range of phenolics (quercetin, p-coumaric acid, rutin, q-coumaric acid, caffeic acid). These analyses clarified that cornelian cherry genotypes have a significant diversity in terms of agro-morphological and phenolic properties of plants; The genetic makeup and activity characteristics, such as altitude, demonstrate how the bioactive and quality traits of cornelian cherry are shaped, providing a critical basis for creating a new product targeted to meet specific market distributions or health fillings.

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