

Evaluation of the Phytochemical Properties of Blueberry (*Vaccinium corymbosum* L.) Fruits

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(Received: 23 January 2026, Accepted: 05 February 2026)

(6th International Conference on Recent Academic Studies ICRAS 2026, January 27-28, 2026)

ATIF/REFERENCE: Çolak, A. M. & Alan, F. (2026). Evaluation of the Phytochemical Properties of Blueberry (*Vaccinium corymbosum* L.) Fruits, *International Journal of Advanced Natural Sciences and Engineering Researches*, 10(2), 27-35.

Abstract – This study was conducted to determine the total phenolic compounds (TPC), total flavonoid compounds (TFC), antioxidant activity (DPPH) and organic acid profiles of blueberry (*Vaccinium corymbosum* L.) fruit extracts. All analyses were performed on a fresh weight (FW) basis. Accordingly, the TPC, TFC and DPPH values were 462.10 mg GAE/L, 380.03 mg QE/L and 83%, respectively. The coefficient of variation (%CV) in TPC and TFC analyses was below 1%, indicating high repeatability of the measurements. Among the phenolic compounds, gentisic acid (53.90 mg 100 g⁻¹) was detected at the highest level, followed by ellagic acid (9.15 mg 100 g⁻¹) and protocatechuic acid (5.94 mg 100 g⁻¹). Regarding organic acids, acetic acid (314.67 mg 100 g⁻¹), oxalic acid (140.67 mg 100 g⁻¹) and tartaric acid (120.67 mg 100 g⁻¹) were identified as the predominant compounds. Examination of the proportional distribution in the total extract revealed that phenolic compounds constituted a smaller fraction overall; gentisic acid was the most abundant phenolic compound (8%), whereas organic acids represented the majority of the extract, with acetic acid (49%) being the key determining compound.

These findings demonstrate that blueberry extracts possess high antioxidant potential and hold significant promise as a functional food. Furthermore, the results provide a scientific basis for a better understanding of the functional properties of blueberries and for the utilization of their bioactive compounds in the food industry.

Keywords – Blueberry, *Vaccinium corymbosum* L., phenolic compounds, organic acids, antioxidant capacity, phytochemical compounds

I. INTRODUCTION

Blueberry (*Vaccinium* spp.), particularly *V. myrtillus*, *V. angustifolium* and *V. corymbosum* species, is a highly nutritious and health-promoting berry due to its rich compounds of phenolic compounds, flavonoids, anthocyanins and organic acids. Anthocyanins, responsible for the fruit's deep blue-purple color, exhibit strong antioxidant properties along with phenolic acids and flavonoids. These bioactive compounds contribute to the neutralization of free radicals, reduction of oxidative stress and enhancement of antioxidant defense systems. Several recent studies have reported that blueberry consumption provides protective effects against chronic diseases associated with oxidative stress and may play a significant role

in preventing cardiovascular diseases, type 2 diabetes and neurodegenerative disorders ([1], [2]). The anti-inflammatory and anticarcinogenic activities of phenolic compounds and flavonoids also strengthen the immune system, highlighting the health benefits of blueberries. A positive correlation between phenolic compounds and antioxidant activity has been reported in different *Vaccinium* genotypes. In this context, the DPPH assay, one of the most widely used methods for determining antioxidant capacity, is commonly applied to evaluate variations in phenolic and flavonoid compounds depending on the ripening stage ([3], [4], [5]). Organic acids are key components that determine the taste, aroma profile and microbial stability of blueberries. In *V. angustifolium* fruits, quinic acid has been reported as the predominant organic acid, followed by citric and malic acids. The organic acid profile varies depending on genotype and cultivation conditions, affecting the shelf life of the fruit ([4], [6]). In the literature, phenolic components, anthocyanin profiles, or antioxidant activities have mostly been evaluated separately ([7], [8]). However, studies simultaneously assessing phenolic compounds, flavonoid level, DPPH and organic acid profile through multiple-replicate analyses are quite limited. Therefore, this study aims to contribute to the literature by simultaneously investigating these parameters to better understand the phytochemical value and potential health benefits of blueberries.

In this context, although phenolic compounds, anthocyanin profiles or antioxidant activity are generally evaluated separately in the current literature, studies that examine these parameters simultaneously under controlled cultivation conditions with multiple replicates are quite limited. Therefore, this study aims to fill this gap in the literature by evaluating the total phenolic content (TPC), total flavonoid content (TFC), antioxidant capacity (DPPH) and organic acid profiles of blueberry fruits concurrently. In addition, the obtained data aim to contribute to a more comprehensive understanding of the phytochemical composition of blueberries and their health benefits.

II. MATERIALS AND METHOD

A. Plant Material

In this study, a single potted blueberry (*V. corymbosum* L.) cultivar was used as the plant material. This study focused on a specific genotype and a single harvest period; all obtained phytochemical values were calculated on a 100 g fresh weight (FW) basis. The plants were grown under semi-open greenhouse conditions in Pursaklar district, Ankara. The growing medium consisted of a mixture of acidic peat, perlite and pine bark (3:1:1) and was filled into pots of approximately 30 L volume. Standard horticultural practices were regularly applied throughout the cultivation period. Fruits were hand-harvested from the same plants at full physiological maturity in July 2025. For each analysis, three replicates were performed; in each replicate, approximately 50 g of fruit sample was homogenized and used for analyses. Before the analyses were conducted, the obtained fruit samples had been stored at -20 °C.

B. Chemical characteristics

Sample Preparation and Extraction

The fruit samples used in the analyses were obtained from fresh fruits stored at -20 °C prior to testing. Approximately 50 g of fruit material was homogenized and extracted for each measurement. For the determination of total phenolic and flavonoid contents, extraction was performed using an 80% methanol solution. The homogenized fruit samples were mixed with methanol at a solvent-to-sample ratio of 1:10 (g/mL) and subjected to processing on a magnetic stirrer at 25 °C for 2 hours. The mixture was then centrifuged for 10 minutes, and the supernatant was filtered to obtain extracts suitable for analysis. This procedure ensured sufficient contact between the samples and the solvent, enabling efficient dissolution of phenolic and flavonoid compounds. Moreover, the same method provided a reliable sample preparation approach for antioxidant and organic acid analyses.

C. Determination of Polyphenol Compounds

The total phenolic compounds of the fruit juice samples were determined using the Folin-Ciocalteu method [9]. Prior to analysis, all samples were passed through a membrane filter and gallic acid was used

as the reference phenolic compound to construct the calibration curve. Methanolic solutions of different concentrations (0-200 µg/mL) were prepared and absorbance measurements were carried out at a wavelength of 765 nm. The calibration equation was $y = 0.0041x - 0.0175$ ($R^2 = 1$). The total phenolic compounds were expressed as mg GAE/L.

Determination of Total Flavonoid Compounds

The total flavonoid compounds of the fruit juice samples were determined using the aluminum chloride ($AlCl_3$)-based colorimetric method [10]. For the analysis, the samples were diluted with distilled water to obtain a final concentration of 500 ppm. To construct the calibration curve, quercetin (QE) solutions at different concentrations (0-100 µg/mL) were prepared in methanol and absorbance measurements were conducted at a wavelength of 415 nm. The total flavonoid compounds were calculated based on the results and expressed as µg QE/L. The calibration equation was $y = 9E-05x - 0.0005$ with a determination coefficient of $R^2 = 0.9993$, indicating excellent linearity. This method allows for the rapid and accurate quantification of flavonoid compounds in the samples.

Phenolic Compounds Analysis by HPLC

The phenolic compounds in the fruit juice samples were analyzed using an Agilent 1260 HPLC system. Chromatographic separation was performed on an ACE-C18 column (4.6 mm x 150 mm, 5 µm particle size), with water containing 0.02% trifluoroacetic acid (TFA) as mobile phase A and methanol containing 0.02% TFA as mobile phase B. The flow rate was set at 0.5 mL/min and the column temperature was maintained constant throughout the analysis. The gradient elution program was as follows: starting with 25% B, increasing to 30% B between minutes 5-10, rising to 45% B between minutes 10-16, held at 45% B between minutes 16-18, increasing to 80% B between minutes 18-25, held at 80% B between minutes 25-30 and finally returning to 25% B between minutes 30-40 [11]. This method allows for detailed and reproducible analysis of the phenolic compounds present in the fruit juice samples.

Quantification of Organic Acids and by HPLC-UV

The organic acids and phenolic compounds in the fruit juice samples were quantitatively analyzed using an Agilent 1260 HPLC system. Chromatographic separation was performed on an ACE-C18 column (4 mm x 150 mm, 5 µm; Hichrom Ltd.). The analysis was carried out using an isocratic elution method with a 10 mM potassium phosphate buffer adjusted to pH 2.2 as the mobile phase. The flow rate was set at 1 mL/min and the injection volume was 20 µL. Detection was performed at 245 nm for ascorbic acid and at 210 nm for other organic acids [12]. This procedure allows for the precise and reproducible quantitative determination of organic acids and phenolic compounds in fruit juice samples.

Antioxidant Activity

The antioxidant activity of the fruit juice samples was determined using the DPPH (2,2-diphenyl-1-picrylhydrazyl) method with slight modifications [13]. The DPPH stock solution (6×10^{-5} M) was prepared by dissolving 0.0024 g of DPPH in 100 mL of methanol. The working solution was diluted with methanol to achieve a concentration of 40 mg/L. For the analysis, 300 µL of fruit juice sample was mixed with 5700 µL of the DPPH solution in 10 mL tubes, vortexed and incubated at room temperature in the dark for 60 minutes. After incubation, absorbance was measured at 517 nm using a Shimadzu UV-1800 UV-Vis spectrophotometer. A control solution, prepared without the sample, was measured at the same wavelength. The percentage of antioxidant activity (AA) was calculated based on the obtained absorbance values using the following formula:

$$\text{Antioxidant activity (\%)} = [(AC(O)_{517} - AA(t)_{517}) / AC(O)_{517}] \times 100$$

Here, $AC(O)_{517}$ represents the absorbance of the control solution at the initial time ($t = 0$) and $AA(t)_{517}$ denotes the absorbance of the sample solution measured after 1 hour.

D. Statistical Analyses

Statistical analyses were performed using IBM SPSS Statistics (v.21.0, IBM Corp., Armonk, NY, USA). All analyses were conducted in triplicate ($n = 3$) and the results are presented as mean \pm standard error (SE), standard deviation (SD) and coefficient of variation (CV%) values (Table 1). Additionally, the proportional contributions (%) of phenolic compounds and organic acids to the total compounds were calculated and their distribution within the extract composition was visualized using a bar chart (Figure 1). Pearson correlation analysis was also performed to evaluate the relationships among all measured phenolic and organic acid compounds and antioxidant activity and the resulting correlation coefficients (r) and significance values (p) are presented in Table 2.

III. RESULTS AND DISCUSSION

Based on the data presented in Table 1, the phenolic and organic acid profiles as well as the antioxidant activities of blueberry (*V. corymbosum* L.) extracts were evaluated in detail. The analyses of blueberry extracts revealed that the total phenolic and flavonoid contents were 462.10 mg GAE/L (SD = 0.66; CV = 0.14%) and 380.03 mg QE/L (SD = 1.65; CV = 0.43%), respectively (Table 1). The DPPH antioxidant activity was determined as 83% (SD = 1.00; CV = 1.20%), indicating a strong antioxidant capacity supported by the contribution of phenolic and flavonoid compounds. These values are consistent with the TPC (410-480 mg GAE L⁻¹) and TFC (350-390 mg QE/L) ranges previously reported by Dragović Uzelac et al. (2010) for *V. corymbosum* [14]. Similarly, the DPPH antioxidant activity of 83% aligns with the high antioxidant activity values reported by Bai et al. (2023) [15]. The high phenolic and flavonoid contents as well as antioxidant activity observed in this study may be shaped by natural variations arising from cultivation conditions, climatic factors, and genetic differences.

Among the phenolic compounds, the highest concentration was observed in gentisic acid (53.90 mg 100 g⁻¹; SD = 2.07; CV = 3.84%), followed by protocatechuic acid (5.94 mg 100 g⁻¹; SD = 0.16; CV = 2.69%). This finding is consistent with previous studies indicating that gentisic acid is a predominant phenolic acid in *Vaccinium* species. Variations observed in the study may be attributed to genetic differences as well as environmental factors such as fruit maturation stage, rainfall levels, and microclimatic conditions ([16], [17]). Compounds detected at lower concentrations, such as caffeic acid (1.70 \pm 0.10 mg 100 g⁻¹; SD = 0.18; CV = 10.59%) and p-coumaric acid (1.78 \pm 0.11 mg 100 g⁻¹; SD = 0.20; CV = 11.24%), exhibited higher CV values, indicating greater biological variability. Ellagic acid, however, showed low variation (9.15 mg 100 g⁻¹; SD = 0.12; CV = 1.31%), suggesting that this component of the phenolic profile may be more genetically stable.

Regarding organic acids, acetic acid (314.67 mg 100 g⁻¹; SD = 9.29; CV = 2.95%) and oxalic acid (140.67 \pm 1.76 mg 100 g⁻¹; SD = 3.06; CV = 2.17%) were identified as the dominant compounds, whereas citric acid was found at the lowest level (1.07 mg 100 g⁻¹; SD = 0.12; CV = 11.21%). The low CV values of acetic and oxalic acids suggest that these acids are phenotypically more stable and less influenced by environmental factors. In contrast, the high CV value of citric acid reflects natural variation associated with genetic diversity and differences in environmental conditions [17], [18].

Overall, these findings demonstrate that blueberries possess a rich phenolic and organic acid composition along with high antioxidant capacity. Furthermore, the observed differences in phenolic and organic acid profiles indicate that both genetic factors such as cultivar and genotype and environmental conditions such as soil characteristics, climate, and cultivation practices play influential roles in shaping the biochemical composition of the fruit. This highlights the importance of carefully managing cultivation and harvest conditions to preserve the high biochemical quality of blueberries.

Table 1. Mean (\pm SE), standard deviation (SD), coefficient of variation (CV%) and range (Min-Max) of phytochemical compounds determined in blueberry (*V. corymbosum* L.) extracts (n = 3).

Variable	Abb.	Unit	Min.	Max.	Compounds (Mean \pm SE, SD)	CV (%)
Total Phenolic Compounds	TPC	mg GAE/L	461.5	462.8	462.10 \pm 0.38, SD = 0.66	0.14
Total Flavonoid Compounds	TFC	mg QE/L	378.4	381.7	380.03 \pm 0.95, SD =1.65	0.43
Antioxidant activity						
Antioxidant activity (DPPH)	AntAc	%	82	84	83 \pm 0.58, SD =1.00	1.20
Phenolic Compounds HPLC						
Protocatechic Acid	ProA	mg 100 g ⁻¹	5.79	6.10	5.94 \pm 0.09, SD =0.16	2.69
Gentisic Acid	GenA	mg 100 g ⁻¹	52.21	56.20	53.90 \pm 1.19, SD =2.07	3.84
Caffeic Acid	CafA	mg 100 g ⁻¹	1.50	1.85	1.70 \pm 0.10, SD =0.18	10.59
Coumaric Acid	CoumA	mg 100 g ⁻¹	1.58	1.97	1.78 \pm 0.11, SD =0.20	11.24
Ellagic Acid	EllA	mg 100 g ⁻¹	9.02	9.24	9.15 \pm 0.07, SD =0.12	1.31
Organic acids						
Oxalic acid	OxaA	mg 100 g ⁻¹	138	144	140.67 \pm 1.76, SD =3.06	2.17
Tartaric acid	TarA	mg 100 g ⁻¹	117	124	120.67 \pm 2.03, SD =3.51	2.90
Acetic acid	AceA	mg 100 g ⁻¹	307	325	314.67 \pm 5.36, SD =9.29	2.95
Citric acid	CitA	mg 100 g ⁻¹	1.0	1.2	1.07 \pm 0.07, SD =0.12	11.21

* Abb: Abbreviation; SE: Standard Error; SD: Standard Deviation; CV: Coefficient of Variation; Min: Minimum; Max: Maximum

According to Table 2, the Pearson correlation analysis of blueberry (*V. corymbosum* L.) extracts revealed strong positive relationships among total phenolic content, total flavonoid content, and DPPH antioxidant activity ($r = 0.99-1.00$). This indicates that the antioxidant capacity increases in parallel with the phenolic and flavonoid levels. Among individual phenolic compounds, gentisic acid and protocatechuic acid exhibited positive correlations with most parameters, whereas caffeic acid showed negative correlations with some compounds (e.g., GenA-CafA $r = -1.00$). Regarding organic acids, acetic acid displayed positive correlations with the majority of phenolic compounds and antioxidant activity, while oxalic and tartaric acids exhibited negative correlations with several parameters ($r \approx -0.99$).

These findings are consistent with those reported by Kim et al. (2025), who demonstrated strong biochemical properties and antioxidant capacity in blueberry extracts, identifying lactic acid as the predominant organic acid and reporting DPPH activity and total phenolic content as 225.03 μ g TEAC/mL and 369.98 μ g GAE/mL, respectively [19]. Furthermore, Xu et al. (2025) reported significant variations in phenotypic and quality traits among blueberry cultivars during postharvest storage, with certain cultivars showing superior stability in color, firmness, and texture [20]. These results support the interpretation that the variations observed in biochemical analyses are associated with inter-cultivar phenotypic and physicochemical differences, and that the biochemical properties of the extracts are influenced by postharvest and storage conditions.

Similarly, Smrke et al. (2025) investigated the effects of photoselective nets of different colors on blueberry fruit quality parameters and chemical composition [21]. They found that fruits grown under black nets exhibited the highest total phenolic, anthocyanin, and petunidin-3-O-glucoside contents, while yellow nets resulted in the lowest sugar/organic acid ratio, and white nets led to reduced total phenolic

content. These findings further demonstrate that biochemical characteristics are influenced by cultivation conditions and align with the outcomes of the present study.

Table 2. Pearson correlation coefficients (r) and significance (p) among phytochemical compounds and antioxidant activity in blueberry (*V. corymbosum* L.) extracts (n = 3).

Variable	Value	TPC	TFC	AntAc	ProA	GenA	CafA	CoumA	EllA	OxaA	TarA	AceA	CitA
TPC	r	1	0.99	0.99	0.62	0.79	-0.78	0.44	-0.03	-0.44	0.54	0.99	0.92
	p		0.07	0.08	0.57	0.41	0.42	0.70	0.97	0.70	0.63	0.07	0.24
TFC	r	0.99	1	1.00*	0.53	0.71	-0.70	.54	-0.15	-0.34	0.44	0.97	0.87
	p	0.07		0.01	0.64	0.48	0.50	.63	0.90	0.77	0.70	0.14	0.32
AntAc	r	.99	1.00*	1	0.51	0.70	-0.69	.56	-0.17	-0.32	0.42	0.96	0.86
	p	0.08	0.01		0.65	0.50	0.51	.62	0.89	0.78	0.71	0.16	0.33
ProA	r	0.62	0.53	0.51	1	0.97	-0.97	-0.41	0.75	-0.97	0.99	0.71	0.87
	p	0.57	0.64	0.65		0.15	0.14	0.72	0.45	0.13	0.06	0.49	0.32
GenA	r	0.79	0.71	0.70	0.97	1	-1.00*	-0.18	0.57	-0.90	0.94	0.86	0.96
	p	0.41	0.48	0.50	0.15		0.01	0.88	0.60	0.28	0.21	0.34	0.16
CafA	r	-0.78	-0.70	-0.69	-0.97	-1.00*	1	0.20	-0.59	0.90	-0.94	-0.85	-0.96
	p	0.42	0.50	0.51	0.14	0.01		.86	0.59	.27	0.20	0.35	0.17
CoumA	r	0.44	0.54	0.56	-0.41	-0.18	0.20	1	-0.91	0.59	-0.50	0.33	0.07
	p	0.70	0.63	0.62	0.72	0.88	0.86		0.27	0.59	0.66	0.78	0.95
EllA	r	-0.03	-0.15	-0.17	0.75	0.57	-0.59	-0.91	1	-0.87	0.81	0.08	0.34
	p	0.97	0.90	0.89	0.45	0.60	0.59	.27		0.32	0.39	0.94	0.77
OxaA	r	-0.44	-0.34	-0.32	-0.97	-0.90	0.90	0.59	-0.87	1	-0.99	-0.52	-0.75
	p	0.70	0.77	0.78	0.13	0.28	0.27	0.59	0.32		0.06	0.62	0.45
TarA	r	0.54	0.44	0.42	0.99	0.94	-0.94	-0.50	0.81	-0.99	1	0.63	0.82
	p	0.63	0.70	0.71	0.06	0.21	0.20	0.66	0.39	0.06		0.55	0.38
AceA	r	0.99	0.97	0.96	0.71	0.86	-0.85	0.33	0.08	-0.55	0.63	1	0.96
	p	0.07	0.14	0.16	0.49	0.34	0.35	0.78	0.94	0.62	0.55		0.17
CitA	r	0.92	0.87	0.86	0.87	0.96	-0.96	0.07	0.34	-0.75	0.82	0.96	1
	p	0.24	0.32	0.33	0.32	0.16	0.17	0.95	0.77	0.45	0.38	0.17	

*. Correlation is significant at the 0.05; Pearson Correlation: r; significance: p

As shown in Figure 1, phenolic compounds constitute a relatively low proportion of the total extract, with gentisic acid representing the highest percentage (8%). This is followed by ellagic acid (1%), protocatechic acid (0.91%), coumaric acid (0.27%) and caffeic acid (0.26%). Organic acids, on the other

hand, make up the majority of the total extract. Acetic acid is the predominant compound (49%), followed by oxalic acid (22%), tartaric acid (19%) and a very low amount of citric acid (0.16%). These results indicate that acetic acid is the main determinant of the organic acid composition, while gentisic acid is the key component in the phenolic compound profile of blueberry extracts. Similar findings are supported by previous studies in the literature. Castrejón et al. (2008) reported that gentisic acid was the dominant phenolic compound in *V. corymbosum* L. fruits grown in China and contributed strongly to DPPH antioxidant capacity [22]. Solcan et al. (2023) noted that ellagic acid was one of the phenolic compounds that increased most during ripening and that the phenolic profile directly affected antioxidant capacity [23]. Regarding organic acids, Zhang et al. (2025) emphasized that oxalic and tartaric acids play a critical role in determining blueberry fruit quality; Rashwan et al. (2023) reported that blueberry (*Vaccinium corymbosum* L.) is rich in bioactive compounds, including anthocyanins, and exhibits notable antioxidant, anti-diabetic, cardioprotective, anti-inflammatory, antimicrobial, and anticancer activities. Accordingly, they indicated that processing blueberries into products such as powder, juice, and wine could be considered a promising strategy to extend shelf-life and enhance health benefits ([24], [25]). In conclusion, the proportional distribution obtained in this study provides important insights into the antioxidant capacity and functional properties of blueberry extracts and is generally consistent with previous research. However, the notably high proportion of acetic acid suggests that factors such as different processing conditions and extraction methods should be investigated in more detail in future studies.

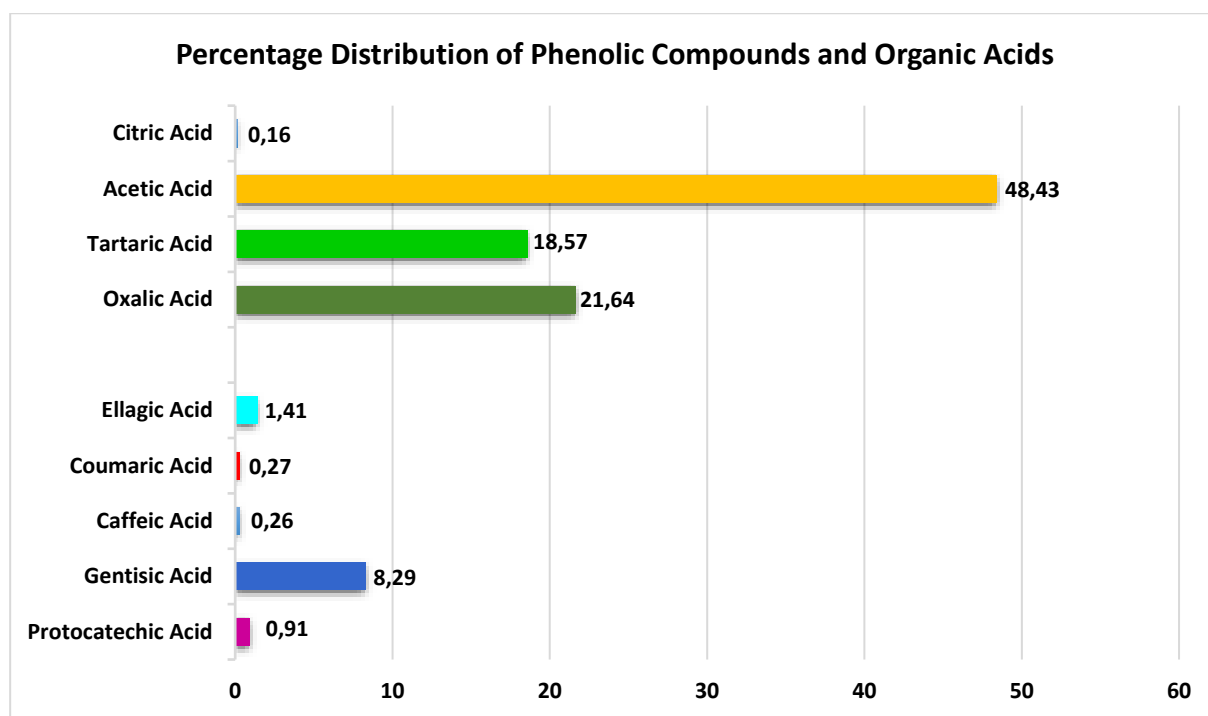


Figure 1. Bar chart showing the proportional distribution (%) of phenolic and organic acid compounds in blueberry (*V. corymbosum* L.) fruit extract based on total compounds (n = 3).

This and similar studies demonstrate that blueberry (*V. corymbosum* L.) fruit is distinguished by its rich phenolic and organic acid profile. As shown in Table 1 and Figure 1, the high proportions of organic acids such as gentisic acid, acetic acid and oxalic acid form the chemical basis of the fruit and contribute to its flavor and durability characteristics. Although phenolic compounds constitute a relatively lower proportion of the extract, they significantly contribute to the antioxidant capacity and play an important role in determining the characteristic color and aroma of blueberries. Furthermore, considering that genetic variation, cultivation conditions and processing methods strongly influence the chemical composition, there is a need for standardized production and processing techniques to preserve the functional properties and enhance the commercial value of blueberries. Future studies are recommended

to focus more in-depth on the bioactivity of phenolic and organic acid components, as well as their changes during storage and processing conditions.

Although the present study provides detailed insights into the phytochemical composition and antioxidant properties of *V. corymbosum* fruits, it should be noted that the analysis was conducted using a single blueberry cultivar and a single harvest period, which may limit the generalizability of the findings. Future studies that include multiple cultivars and harvest seasons would be valuable for validating and expanding upon these results.

IV. CONCLUSION

This study provides a significant scientific contribution to *V. corymbosum* research by elucidating the influence of phenolic and organic acid constituents on antioxidant capacity, as well as their roles in fruit quality and functional properties. The findings offer a critical foundation for plant breeding programs aimed at selecting and developing genotypes with high biochemical potential. The observed variability in phenolic and organic acid profiles among genotypes indicates that these components can be effectively utilized in targeted optimization and genetic selection strategies. Moreover, the interaction between genetic variation, cultivation practices, and environmental factors represents an essential consideration for enhancing the functional and nutritional value of the fruit. In this context, plant breeding efforts may incorporate not only fruit yield but also biochemical composition and functional attributes as key selection criteria. The outcomes of this study contribute to the development of strategies to optimize phenolic and organic acid compositions in blueberry genotypes, thereby providing guidance for both scientific literature and applied breeding practices. Future research focusing on genotype–environment interactions and the effects of cultivation conditions on phenolic and organic acid profiles will further enable the transformation of laboratory-based findings into practical, field-applicable approaches and breeding plans.

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