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Chemical, polyphenolic, and technological characterization of the Sev Areni grape variety and its clones: Implications for wine quality parameters

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ABSTRACT

Background: The Areni grape (*Vitis vinifera* L.) is an indigenous Armenian variety renowned for its adaptation to local terroir and historical significance in winemaking. Its genetic diversity, particularly among clones, offers valuable resources for enhancing wine quality through variations in phenolic compounds, chemical composition, and technological traits. Understanding these differences is crucial for selecting optimal genotypes in viticulture and enology, especially in regions like Armenia, where traditional varieties contribute to unique wine profiles.

Objective: To assess the chemical, polyphenolic, and color variations among three Areni grape genotypes and their impact on wine quality indicators.

Methods: Analyses of grapes and wines produced under microvinification conditions were performed according to OIV standards, using spectrophotometry and HPLC to determine organic acids, physicochemical parameters, total phenolics, anthocyanins, flavonoids, and color indices.

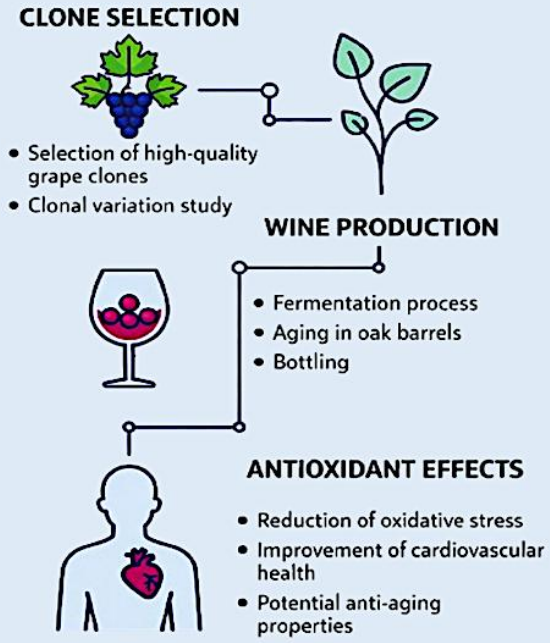
Results: Nosr Areni displayed the highest pigment content in the fruit, Areni clone 15 produced wines with the highest total phenolics, and Sev Areni wines exhibited the greatest color intensity. Chemical parameters varied depending on the specific genotype characteristics.

Conclusion: Areni genotypes exhibit pronounced biochemical and technological diversity, which significantly influences wine composition and color development. Areni clone 15 stands out for its high phenolic potential, making it a promising raw material to produce high-quality red wines.

Novelty of the Study: This study provides the first comparative evaluation of Sev Areni and its clones in terms of polyphenolic composition and wine quality, identifying clones with high phenolic potential and technological suitability for winemaking.

Keywords: Sev Areni grape, Vitis vinifera, polyphenols, anthocyanins, flavonoids, organic acids, wine color, clonal selection

Graphical abstract: Clonal Selection and Antioxidant Potential of Sev Areni Grapes



Graphical Abstract: Chemical, polyphenolic, and technological characterization of the Sev Areni grape variety and its clones: Implications for wine quality parameters

INTRODUCTION

Armenia, as one of the oldest regions of viticulture and winemaking, is distinguished by high ampelographic diversity. The country hosts more than 400 indigenous grape varieties, among which "Areni" holds strategic importance for red wine production. Under conditions of genetic erosion, it is crucial not only to preserve and rejuvenate traditional varieties in Armenia but also to scientifically assess their chemical composition, particularly the polyphenolic profile, for modern nutritional and health-related purposes [1].

Over the past two decades, scientific interest in polyphenols, especially compounds derived from grapes and wine, has increased significantly due to their substantial health and technological significance. Grapes and wine are rich sources of bioactive phenolic compounds, which not only shape the wine's organoleptic characteristics but also provide various protective effects in the human body [2-3].

Polyphenols—including catechins, procyanidins, anthocyanins, and their derivatives—are particularly abundant in red grapes and wines. These compounds are well known for their antioxidant, anti-inflammatory, and free radical–scavenging properties [4-5]. These bioactive compounds are associated with a reduced risk of various chronic diseases, including cardiovascular disorders, diabetes, atherosclerosis, and certain cancers [6-7].

Epidemiological and clinical studies suggest that moderate red wine consumption (approximately 100–150 mL/day) is associated with cardiovascular benefits, including improved endothelial function, favorable modulation of lipid profiles, and support for cellular redox homeostasis [8-9]. Procyanidins, among the most abundant polyphenols in red wine, have been shown to increase HDL-cholesterol levels, reduce LDL-cholesterol oxidation, and upregulate genes involved in hepatic cholesterol metabolism, thereby contributing to atherosclerosis prevention [10].

Beyond cardiovascular effects, wine polyphenols influence gut microbiota composition, promoting the growth of beneficial bacteria and the production of anti-inflammatory short-chain fatty acids. These effects are particularly relevant for preventing metabolic disorders, including insulin resistance and type 2 diabetes. Furthermore, both in vitro and animal studies have demonstrated the hepatoprotective potential of wine polyphenols, evidenced by reduced serum AST and ALT levels and enhanced activity of endogenous antioxidant enzymes [1,3].

The quantitative and qualitative polyphenolic composition of grapes and wine is influenced by numerous factors, foremost among which are grape variety and clonal genetic makeup [12], followed by viticultural practices and winemaking techniques. Within *Vitis vinifera* L., considerable intra-varietal genetic and phenotypic diversity exists [13-14], resulting in distinct polyphenolic profiles that can be exploited through targeted clonal selection to produce wines with enhanced sensory characteristics and potential health benefits.

Consequently, detailed characterization of varietal and clonal differences in polyphenolic composition is essential to fully exploit the technological and functional potential of indigenous grape varieties and to guide the development of high-quality, polyphenol-rich wines.

MATERIALS AND METHODS

For this study, the Sev Areni grape variety and two of its clones—Nosr Areni and Areni clone 15—were used. The plant material was sourced from a collection vineyard dedicated to the conservation of autochthonous Armenian grapevine cultivars, located in Ejmiatsin (Armenia) at an altitude of 870 m above sea level.

Sev Areni is a late-ripening red wine grape variety capable of yielding 8–15 t/ha under standard cultivation conditions. It is characterized by compact clusters, thick-skinned berries with high phenolic content, resulting in a relatively low must yield and modest sugar accumulation. These traits limit its technological efficiency for winemaking [15].

Areni clone 15 exhibits high enological potential due to its larger berry size, higher juice (must) yield, and improved berry texture. These characteristics make it particularly promising to produce premium-quality wines.

Nosr Areni stands out for its exceptionally high must yield and a lower proportion of skins and seeds (pomace), resulting in higher sugar concentration in the must—a key distinguishing feature of this clone.

Winemaking: Grapes were harvested manually in autumn 2024 at technological maturity. Harvesting was performed according to standard protocols using small-volume plastic crates to minimize mechanical damage and preserve berry integrity.

Immediately after harvest, berries were assessed for technological maturity. The following physicochemical parameters were determined: total soluble solids (°Brix), titratable acidity (g/L tartaric acid), pH, and other relevant indices. These data served as the basis for a comparative evaluation of the variety and its clonal selections.

Microvinification was carried out at the Experimental Laboratory of Enology and Fermentation Technology, at the Armenian National Agrarian University, following a standardized red winemaking protocol with minor adaptations. Grapes were destemmed and crushed, and the resulting mash (pomace + must) was transferred into temperature-controlled stainless-steel fermentors.

Fermentation was initiated by the addition of dry active Saccharomyces cerevisiae yeast (strain AS-2) at a dose of 30 g/hL, together with a sugar supplementation of 30 g/L (3 g/dL) to adjust the potential alcohol. Alcoholic fermentation combined with maceration was conducted at 25 ± 1 °C for 10 days. The cap was punched down twice daily to ensure homogeneous extraction of phenolic compounds and color [16].

At the end of alcoholic fermentation, the free-run wine was separated, and the pomace was gently pressed using a basket press. The resulting press wine was combined with the free-run fraction. The young wine was then racked off the gross lees, sulfited with 50 mg/L SO_2 (as potassium metabisulfite), and transferred to a settling tank for cold stabilization and maturation.

Chemical Analysis: Grapes and wines were analyzed in accordance with the official methods of the International Organization of Vine and Wine (OIV) [17]. The sugar content of grapes was determined by refractometry. Ethanol content was quantified using the OIV-MA-AS312-01A method, whereas total acidity was measured according to the OIV-MA-AS313-01 protocol. Must acidity indices were determined according to the OIV-MA-AS313-02 method. Free and total sulfur dioxide concentrations were determined using the OIV-MA-AS315-27 (previously OIV-MA-F1-07) method, and the profile of organic acids was characterized by high-performance liquid chromatography (HPLC) [18-19].

The HPLC analysis was performed using a mobile phase consisting of ultrapure water supplemented with 0.5% ethanol and 0.0139% concentrated sulfuric acid. The column temperature was maintained at 46 °C. Detection was performed using a variable-wavelength UV detector set at 210 nm in series with a refractive index detector. The system was equipped with an online vacuum degasser and a binary pump delivering a constant flow rate of 0.6 mL/min. The injection volume was 10 mL.

Total Phenolics: The total content of phenolic compounds was determined using a spectrophotometric colorimetric method [20]. First, 100 grape berries were homogenized using an Ultra-Turrax T25 device at high speed for 3 minutes. Then, 10 g of the homogenate was mixed with 10 mL of hydrochloric ethanol solution and incubated at 20 °C for 30 minutes. The sample was subsequently centrifuged at 5000 × g for 10 minutes, and the supernatant was collected in a 10 mL volumetric tube. The sample volume was adjusted to 50 mL with

hydrochloric ethanol solution. Wine samples were pre-diluted using the same solution.

The concentrations of anthocyanins and flavonoids were determined via spectrophotometric analysis in the UV–visible spectral range of 230–700 nm.

RESULTS AND DISCUSSION

Citric Acid: The antioxidant and antibacterial effects of citric acid highlight the importance of its continuous monitoring. As a key activator of the tricarboxylic acid (TCA) cycle, citric acid also participates in numerous metabolic processes of microorganisms [21].

During grape maturation, citric acid content decreases due to its biochemical conversion into malic acid, resulting in low levels in fully ripe berries [22–25]. Among the genotypes studied, citric acid content was highest in Sev Areni (0.14 g/L), followed by Nosr Areni (0.12 g/L), and lowest in Areni clone 15 (0.09 g/L). Despite its low concentration, citric acid contributes to the expression of fruity aromas and can readily participate in secondary fermentation processes.

Tartaric Acid: The chemical stability of wine is largely ensured by tartaric acid, which also plays an important role in color and flavor development [26]. Tartaric acid synthesis begins during the cell division phase of grape berries and continues throughout maturation [27–28].

The highest tartaric acid content was recorded in Nosr Areni (7.51 g/L) and Sev Areni (7.48 g/L), whereas Areni clone 15 exhibited a lower level (5.21 g/L), characteristic of its mild and soft acidity. This feature may help maintain wine freshness and balance, making it suitable for various styles and flavor profiles. Tartaric acid is recognized as one of the main strong acids in wine, contributing to chemical stability and enhancing storage potential [29].

Malic Acid: The highest malic acid concentrations were observed in Sev Areni grapes (1.18 g/L) and Areni clone 15 (1.16 g/L), while Nosr Areni showed significantly lower levels (0.69 g/L). Malic acid plays a key role in malolactic fermentation, during which it is converted into lactic acid, thereby reducing overall wine acidity while enhancing stability and softening aromatic profiles [30–32].

Fumaric Acid: Fumaric acid content was nearly identical in Sev Areni (0.004 g/L) and Areni clone 15 (0.004 g/L), whereas Nosr Areni contained slightly less (0.002 g/L).

Table 1: Analysis of the Organic Acids in the Sev Areni Grape and its Clones.

Organic acids	Unit of measurement	Grape		
		Sev Areni	Nosr Areni	Areni clone 15
Tartaric acid	g/l	7.48 ± 0.03	7.51 ± 0.03	5.21 ± 0.03
Formic acid	g/l	0.06 ± 0. 01	0.00	0.013 ± 0.01
Malic acid	g/l	1.18 ± 0. 02	0.69 ± 0. 02	1.16 ± 0. 02
Shicimic acid	g/ l	-	-	-
Lactic acid	g/ l	-	-	-
Acetic acid	g/ l	-	-	-
Citric acid	g/ l	0.14 ± 0.04	0.12 ± 0.03	0.09 ± 0.04
Succinic acid	g/ l	-	-	-
Fumaric acid	g/ l	0.004 ± 0	0.002 ± 0	0.004 ± 0

The principal physicochemical characteristics of berries and dry wines from the three Areni genotypes (Sev Areni, Nosr Areni, and Areni clone 15) are summarized in Table 2.

Table 2: Standard Physicochemical Parameters of Grape and Wines.

Parameters	Unit of measurement	Grape			Wine		
		Sev Areni	Nosr Areni	Areni clone 15	Sev Areni	Nosr Areni	Areni clone 15
Sugar	Brix, %	18.3 ± 0.3	19.8 ± 0.4	17.9 ± 0.2	-	-	-
Total acidity	g/l	5.12 ± 0.02	5.44 ± 0.03	4.74 ± 0.01	3.98 ± 0.01	4.74 ± 0.015	3.98 ± 0.01
(pH)	-	3.58 ± 0.015	3.5 ± 0.01	3.67 ± 0.02	3.75 ± 0.02	3.43 ± 0.015	3.7 ± 0.018
Alcoholic strength	%	-	-	-	11.1 ± 0.4	10.4 ± 0.3	8.8 ± 0.2
Reducing sugar	g/l	-	-	-	0.15 ± 0.015	0.15 ±0 .015	0.15 ± 0.015
Volatile acidity	g/l	-	-	-	0.68 ± 0.015	0.58 ± 0.01	0.7 ± 0.02
Aldehydes	mg/l	-	-	-	23.76 ± 0.2	24.2 ± 0.3	22.88 ± 0.1
Acetals	mg/l	-	-	-	30.68 ± 0.3	35.4 ± 0.4	37.76 ± 0.5
Free SO2	mg/l	-	-	-	7.36 ± 0.25	8 ± 0.3	7.04 ± 0.2
Total SO2	mg/l	-	-	-	31.36 ± 0.3	33.28 ± 0.4	29.44 ± 0.25
Reductions SO2	mg/l	-	-	-	3.84 ± 0.21	3.84 ± 0.21	3.2 ± 0.15

Grape soluble solids content, determined by refractometry, ranged from 17.9 to 19.8 °Brix. Nosr Areni recorded the highest value (19.8 ± 0.2 °Brix), whereas Areni clone 15 exhibited the lowest (17.9 ± 0.2 °Brix). Titratable acidity (expressed as g/L tartaric acid) was highest in Nosr Areni (5.44 ± 0.01 g/L) and lowest in Areni clone 15 (4.74 ± 0.01 g/L). Must pH varied between 3.50 and 3.67, with Nosr Areni showing the lowest value (3.50 ± 0.01) and Areni clone 15 the highest (3.67 ± 0.01).

All wines were fermented to dryness, with residual sugar concentrations ≤ 0.15 ± 0.015 g/L. Ethanol content ranged from 8.8 ± 0.2% vol (Areni clone 15) to 11.1 ± 0.2% vol (Sev Areni). Wine pH increased slightly relative to the corresponding musts and ranged from 3.43 ± 0.015 (Nosr Areni) to 3.75 ± 0.015 (Sev Areni). Titratable acidity decreased during fermentation and vinification, falling between 3.98 ± 0.02 g/L and 4.74 ± 0.02 g/L.

Volatile acidity (expressed as g/L acetic acid) remained well within OIV limits (< 1.2 g/L), ranging from 0.58 ± 0.02 g/L to 0.70 ± 0.02 g/L. Total aldehyde content ranged from 22.9 ± 0.1 mg/L to 24.2 ± 0.1 mg/L, while acetal concentration was markedly higher in Areni clone 15 wine (37.8 ± 0.2 mg/L), which potentially enriches aromatic complexity.

Free SO_2 concentrations ranged from 7.0 ± 0.3 mg/L to 8.0 ± 0.3 mg/L, and total SO_2 from 29.4 ± 0.3 mg/L to 33.3 ± 0.3 mg/L. These levels provide adequate microbiological and oxidative protection without exceeding sensory thresholds or requiring excessive sulfiting. Bound (reducible) SO_2 was lowest in Areni clone 15 wine (3.2 ± 0.2 mg/L) and reached 3.8 ± 0.2 mg/L in both Sev Areni and Nosr Areni wines.

Polyphenols have attracted considerable scientific interest owing to their well-documented health-promoting properties, particularly their potent antioxidant activity. By scavenging free radicals and mitigating oxidative stress, these compounds are implicated in preventing chronic diseases such as cardiovascular disorders, cancer, and neurodegeneration [34–36].

Red-skinned grape varieties and their wines are especially rich in polyphenols, among which anthocyanins play a central role. These vacuolar pigments, synthesized and accumulated primarily in the

hypodermal cells of the berry skin, are responsible for red coloration. Their concentration and profile are strongly influenced by genotype, terroir, viticultural practices, and winemaking techniques [37-38]. During ripening and subsequent vinification/ageing, anthocyanins undergo progressive polymerization with tannins — a reaction frequently mediated by acetaldehyde — leading to a shift from bright red toward more stable brick-orange hues.

Beyond their sensory significance, plant polyphenols serve critical ecological functions, including protection against UV radiation, microbial pathogens, and herbivory [39–43].

The results of this study demonstrated that the highest anthocyanin concentration in grape berries was recorded in the Nosr Areni clone, reaching 953.99 mg/L, which was substantially higher compared with the Sev Areni (705.13 mg/L) and Areni clone 15 (505.06 mg/L). However, the anthocyanin content in the resulting wines decreased markedly, amounting to 110.2 mg/L, 72.4 mg/L, and 37.3 mg/L, respectively. This corresponds to extraction efficiencies of 11.55%, 10.26%, and 7.38%. These findings confirm that the transfer of anthocyanins from the grape skin into wine is strongly influenced by varietal characteristics, skin morphology, and technological factors, such as maceration duration, fermentation conditions, and temperature.

Table 3: The Total Anthocyanin, Flavonoids, Phenolic Compounds, and Color Composition of the Sev Areni Variety and its Clones' Grapes and Wines.

Compounds	unit of measurement	Grape						Wine		
		Sev Areni	Extrac-table	Nosr Areni	Extrac-table	Areni clone 15	Extrac-table	Sev Areni	Nosr Areni	Areni clone 15
Total anthocyanins	mg/l	705.13 ± 2.1	505.06 ± 1.8	953.99 ± 2.8	442.52± 1.6	600.06± 1.9	168.99 ± 0.9	72.4 ± 0.4	110.2± 0.6	37.3 ±0.3
Total flavonoids	mg/l	2354.3 ± 4.2	1059.4 3 ±3 .1	3997.0 1 ± 5.4	1188.46 ± 3.3	3366.34 ± 4.7	912.3± 2.7	340.6 ± 1.9	1549.9 ± 3.5	417.7± 2.1
The total content of phenolic compounds	mg/l	-	-	-	-	-	-	646.84 ±2.3	548.14 ± 2	1425.01 ± 3.2
Folin checaltau index	-	-	-	-	-	-	-	15.46 ± 0.5	26.20± 0.7	34.05± 0.9
Chromatic characteristics										
Color intensity	-	-	-	-	-	-	-	33.2 ± 0.7	4.6 ± 0.1	14.8 ± 0.3
Color shade	-	-	-	-	-	-	-	1.34 ± 0.4	0.89 ±0.3	1.38 ± 0.45
Color composition										
Yellow	%	-	-	-	-	-	-	50.08 ± 2.1	38.6 ± 1.6	49.3 ± 1.9
Red	%	-	-	-	-	-	-	37.44 ± 0.9	43.4 ± 1.1	37.0 ± 0.75
Blue	%	-	-	-	-	-	-	12.5 ± 0.3	17.9 ± 0.45	13.7 ± 0.35

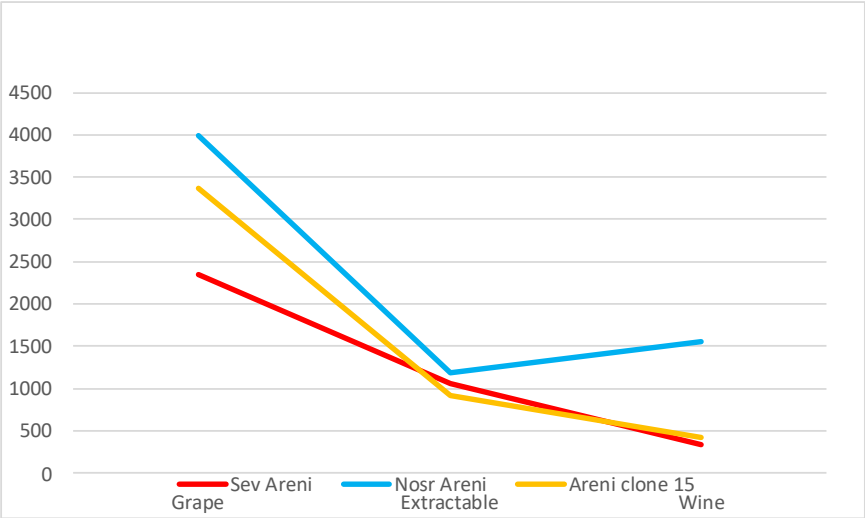


Figure 1. Dynamics of Anthocyanin content in the Sev Areni Grape Variety and its Clones from Grape to Wine.

Similar trends have been reported in several international studies. Bautista-Ortín et al. [44] demonstrated that, in red grape varieties, the extraction of anthocyanins from the skins into wine is inherently partial and depends on cultivar-specific traits and cellular structure. According to their data, the proportion of anthocyanins transferred from skins to wine typically does not exceed 10–20%, even under extended maceration conditions [44].

More recent investigations of red grape varieties cultivated on the eastern foothills of the Helan Mountains in China have similarly highlighted substantial disparities between anthocyanin concentrations in grape skins and the finished wines. Chen et al. [45] reported skin anthocyanin levels ranging from 800 to 1,200 mg/kg fresh weight, while the corresponding wines contained only 80–180 mg/L, yielding extraction efficiencies of 8–15%. Analogous observations emerge from studies on diverse red varieties, underscoring that elevated anthocyanin accumulation in grape skins does not invariably translate to commensurate levels in wine [44-45].

Comparing these data with our results, it is evident that the 11.55% extraction efficiency recorded in Nosr Areni aligns with the range reported in the international literature and is relatively high compared to other varieties. This could be attributed to the high permeability of this variety's berry skin, specific cellular structural features, and more intensive pigment extraction during the maceration phase. Furthermore, as shown by Setford et al., the mass transfer of anthocyanins is limited not only by diffusion but also by convective flows and adsorption onto the surfaces of skins and seeds [46].

Thus, our findings add to the existing literature on anthocyanin extractability in red wines and highlight the importance of varietal differences. The high transfer efficiency observed in Nosr Areni indicates that this genotype has strong pigmentation potential and good technological suitability for producing wines with pronounced color intensity.

The highest flavonoid concentration in grape berries was recorded in Nosr Areni (3997.01 mg/L), followed by Areni clone 15 (3366.34 mg/L) and Sev Areni (2354.3 mg/L). In the corresponding wines, flavonoid levels were 1049 mg/L, 417.7 mg/L, and 340.6 mg/L, with transfer efficiencies of 26.26%, 12.4%, and 14.46%, respectively.

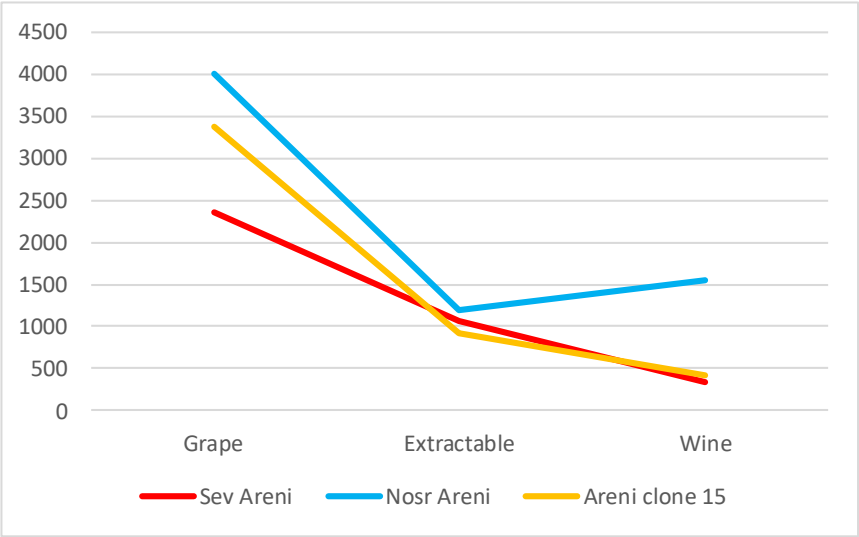


Figure 2. Dynamics of Flavonoid Content in the Sev Areni Grape Variety and its Clones from Grape to Wine.

These results are consistent with international reports. Grigoryan et al. [35] documented average transfer rates of 20–30% in the Areni variety, depending on viticultural and technological conditions. Yu et al. [47] reported mean transfer efficiencies of 15–25% across several cultivars. Similarly, Bai et al. observed transfer percentages ranging from 18–27% across four red grape varieties [35,47-48].

Thus, the high transfer rate observed in the Nosr Areni clone is comparable to that of the most efficient international varieties, whereas Sev Areni and Areni clone 15 display considerably lower values, likely due to structural characteristics of the berry skin and technological factors. This highlights the technological potential of Nosr Areni as a variety with a strong phenolic profile.

In this study, the total phenolic content in wines was determined using the Folin–Ciocalteu method, which is widely applied as an international standard for the quantitative assessment of phenolic composition in wines [43]. The highest concentration was recorded in the wine of Areni clone 15 (1425.01 mg/L), followed by Sev Areni (646.84 mg/L), while the lowest value was observed in Nosr Areni (548.14 mg/L). These variations reflect substantial varietal differences driven by the structural properties of pigments and tannins, as well as differences in extraction efficiency.

According to international studies, the total phenolic content in red wines typically ranges from 500 to 1800 mg/L, depending on cultivar, fermentation parameters, and technological approach. For instance, Yu et al. reported phenolic concentrations of 750–1600 mg/L in wines of three Chinese cultivars, while Shijian Bai et al. found levels between 620–1450 mg/L—values that align well with our results [47–48].

Setford et al. demonstrated that varietal differences and structural characteristics of grape skins play a decisive role in shaping the total phenolic content of the final wine [46]. According to our data, the elevated phenolic concentration in Areni clone 15 is comparable to that of highly pigmented international varieties, whereas Sev Areni and Nosr Areni fall within moderate ranges [46].

These findings indicate that Areni clone 15 possesses strong technological potential to produce phenolic-rich wines.

Spectrophotometric assessment of color intensity and chromatic characteristics revealed substantial differences among the studied wines. The highest color intensity was recorded in Sev Areni (33.2 units), followed by Areni clone 15 (14.8 units), while the lowest value was

observed in Nosr Areni (4.6 units). The hue index ranged from 0.89 to 1.38, with the highest value in Areni clone 15 (1.38), indicating a predominance of yellow pigments. In contrast, Nosr Areni showed a dominance of red pigmentation, which is typical of young wines or varieties rich in monomeric pigments.

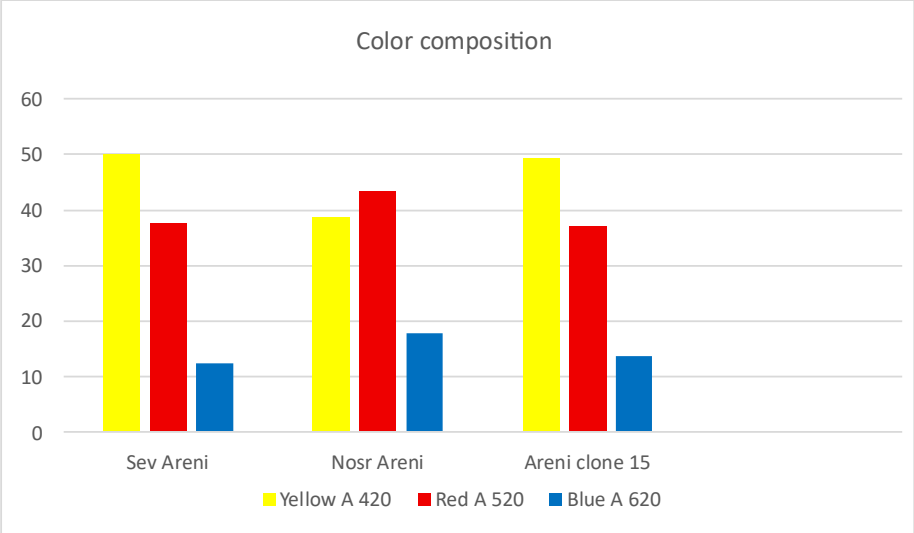


Figure 3. Color Composition of Wine Samples

Analysis of pigment proportions demonstrated that red pigment content was highest in Nosr Areni (43.4%), followed by Sev Areni (37.44%) and Areni clone 15 (37.0%). The proportion of blue pigment was also greatest in Nosr Areni (17.9%), whereas yellow pigment was most pronounced in Areni clone 15. These findings indicate that wine color formation is determined not only by the total anthocyanin content but also by their structural forms, degree of polymerization, and varietal specificity.

International studies confirm these trends. In the study by Uysal et al., the color intensity of "Monastrell" wines ranged between 10 and 30 units, while the hue index ranged from 0.85 to 1.45 [49]. He et al. demonstrated that young wines have a higher proportion of red/blue pigments, whereas the increase in yellow pigment is associated with polymerization and maturation [50]. Studies on Syrah wines have shown that intensity can reach 25–35 units, and hue changes depend on skin maceration techniques [51]. Gordillo et al. confirmed that the ratio of blue to red pigments can be used as a varietal identification tool [52]. Research has shown that in young wines, the proportion of blue pigment averages 10–20%, whereas during maturation, the yellow fraction increases up to 50% [52].

Furthermore, Rao et al. demonstrated that optimization of technological conditions (temperature, maceration duration, pH) can significantly increase anthocyanin extraction levels and intensity [53]. Research on Pinot Noir wines has shown that polymerized pigments are responsible for increased intensity and prolonged color stability [54].

Overall, our results are consistent with international data: the higher proportion of red and blue pigments in Nosr Areni is characteristic of young wines, whereas the higher hue index in Areni clone 15 corresponds to wines dominated by polymerized pigments. These differences are important for identifying varietal characteristics and optimizing winemaking technologies.

Furthermore, these findings align with quantum and temporal theories in functional food science, which emphasize the dynamic, time-sensitive mechanisms through which polyphenolic compounds in functional foods like wine exert their health-promoting effects,

thereby supporting the development of polyphenol-enriched products for nutritional and therapeutic purposes.

This study aligns with the Functional Food Center's (FFC) 17-step model for introducing functional foods to the market, particularly steps 2 and 3, by determining relevant bioactive compounds (e.g., polyphenols, anthocyanins, and flavonoids) in Areni grape genotypes and establishing their concentrations through comparative analysis. Additionally, it supports step 7 by evaluating grapes and wines as appropriate food vehicles for delivering these compounds, which have enhanced health-promoting properties, such as antioxidant and anti-inflammatory effects. These findings provide a foundational basis for developing phenolic-rich wines as functional foods, contributing to personalized nutrition strategies aligned with the quantum and temporal principles of functional food science [55-60].

CONCLUSION

The present study demonstrated that the genotypic diversity of Areni grapes generates significant biochemical and technological differences that decisively shape wine's polyphenolic composition, pigment stability, and color intensity. Nosr Areni stood out for its high pigment potential, Areni clone 15 for a richer overall phenolic profile, while Sev Areni provided the highest color intensity values. These results highlight the critical importance of clonal variability in anthocyanin extraction, pigment polymerization, and the development of the wine's sensory structure. Overall, the data provide a scientific basis for targeted clonal selection of the Areni variety and for optimizing the production of high-quality, phenolic-rich Armenian red wines.

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