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Agronomic performance and berry composition of four *Cabernet Sauvignon* clones under semi-arid viticultural conditions

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Abstract. Clonal variability in *Cabernet Sauvignon* provides an opportunity to optimized wine yield and oenological potential under semi-arid conditions where limited water availability and high temperatures can affect grape composition. In this study, we evaluated the agronomic performance and berry characteristics of four clones (7, 15, 169, and 685) grafted onto Paulsen 1103 rootstocks during two consecutive seasons in Argentina. Measurements included plant water status, leaf area, yield components, and berry composition, with particular emphasis on polyphenols and anthocyanins. While no differences in stem water potential were detected, stomatal conductance revealed distinct water-use efficient strategies among clones. Clone 7 showed the highest fertility and productivity but lower polyphenolic content (35% less *malvidin 3-glucoside* than clone 685), while clone 685 consistently accumulated the highest anthocyanin concentrations despite its lower yield (26% less than 7). Clone 169 combined relatively high yields with intermediate berry composition, while clone 15 showed the lowest productivity with moderate quality parameters. These findings demonstrate that genetic variability among *Cabernet Sauvignon* clones grown under semi-arid conditions influences both agronomic performance and fruit composition, providing winegrowers with valuable tools for a given environment and to adapt vineyard management to future climate change scenarios.

Key words: semi-arid conditions, yield, quality, anthocyanins.

INTRODUCTION

Cabernet Sauvignon is a French wine grape cultivar recognized worldwide for producing high quality. In Argentina, it is one of the most important winemaking varieties (INV, 2024). Being mid- to late-season, *Cabernet Sauvignon* has a long vegetative cycle and requires many hours of warm sunshine and hot days, allowing it to adapt to semi-arid climates. Climatic conditions together with soil and plant material define the *terroir*, which influences not only vine growth and fruit quality but also the quantitative and qualitative composition of polyphenolic and aromatic compounds

(Van Leeuwen, 2004; Van Leeuwen & Seguin, 2006; Tomasi et al., 2013; Drappier et al., 2017; Deis et al., 2024; Rafique 2024a, 2024b; Rafique et al., 2025a). In semi-arid reigns, the amount of water and high temperatures found reduce the concentration of health promoting polyphenolic and aroma compounds (Wolpert et al., 2002; Shah et al., 2021; Rafique et al., 2023a).

Genotype factors modify plant phenolic composition in grapes and wines. Numerous studies have highlighted the differences between *Cabernet Sauvignon* clones and wine quality, fruit aroma, and tannin and anthocyanin concentration (Dejeu, 1986; Jones & Davis, 2000; Fidelibus et al., 2006; Filip et al., 2018). The clonal variability provides producers with a tool to characterize their wines and to mitigate the effects of climate change while maintaining the same cultivars in the same areas (Medrano et al., 2002; Faralli et al., 2024).

Rising temperatures and increased frequency of extreme events such as droughts, among others, are attributed to climate change (Rafique et al., 2023a). Consequently, clonal variability is a powerful tool for mitigating climate change, as clones may maintain typicity and varietal characteristics despite climate change (Medrano et al., 2002).

To identify clones that are more adaptable to climatic conditions, it is necessary to study the qualitative and quantitative characteristics (sugar, acidity, aromas, and polyphenolic compounds) of the different clones (Hopf et al., 2022; Rafique et al., 2025a). Physiological characteristics such as water status, yield components, berry size, exposed leaf area, growth (Anjum et al., 2020; Rafique et al., 2024a; Anjum et al., 2025) etc. are closely related to the quality of grapes berries.

The water status of the plant during grape ripening determines the quantity and polyphenol profile of the grape and, consequently, of the wine. The effect on yield and quality depends on the timing, intensity, and duration of the water stress period (Ojeda et al., 2002). Water deficit induces stomatal closure limiting CO_2 uptake for photosynthesis, decreasing carbon fixation, yield, sugar content, and polyphenol content in berries. Several abiotic stress factors affecting the grapevine also affect the synthesis of chlorophyll and secondary metabolites, causing, among other things, reduced and delayed grape ripening (Pirie & Mullins, 1980; Hall et al., 2002; Hyvönen et al., 2003; Ortega-Regules et al., 2006; Deis et al., 2011; Malovini et al., 2019; Shah et al., 2021). One way to quantify stress in the field would be to measure chlorophyll content using non-destructive measurements based on red and infrared absorbance (SPAD) (Brunetto et al., 2012; Muñoz-Huerta et al., 2013; Rafique et al., 2023b). Leaf chlorophyll content is also a reliable indicator of soil nitrogen availability and the variability of soil nitrogen content within a single vineyard. The total leaf area exposed to sunlight also affects fruit ripening (Kliewer & Dokoozlian, 2005). Previos studies determined that in Cabernet Sauvignon, 0.8 to 1.2 m^2 of leaf area per kilogram of fruit is required for adequate ripening when using a single-canopy trellis training system (Kliewer & Dokoozlian, 2005). Recent research revealed that a pruning weight yield of between 4 and 10 was generally required for adequate fruit ripening. It has also been reported that 2 to 5 m^2 of leaf area (m^2) per m^2 of canopy length are required to produce high-quality fruit and wine (Kliewer & Dokoozlian, 2005; Keller et al., 2005). The ratio between leaf area and fruit weight is a key indicator of plant balance (Howell, 2001) and values between 7 to 14 cm^2 per gram of fruit is adequate for good industrial and polyphenolic ripening (Howell et al., 1987). Among the polyphenolic compounds that contribute to the phenolic

characteristics of wines are anthocyanins, tannins, and flavonoids. The objective of this study was to evaluate the agronomic behavior and oenological aptitudes of four *Cabernet Sauvignon* clones over two consecutive seasons under semi-arid conditions.

MATERIALS AND METHODS

Plant material

This study was conducted in a commercial vineyard located in Mendoza, Argentina, on 15-year-old plants. Measurements were carried out during two consecutive seasons on 4 different Cabernet Sauvignon clones (7, 15, 169, 685), grafted on Paulsen 1103 rootstock. The experimental design was a randomized complete block design with 5 replicates and the experimental unit consisted of 5 plants.

Meteorological data were recorded throughout the two growing seasons using an automated weather station located within the vineyard. Sensors measured air temperature, relative humidity, solar radiation, and precipitation at hourly intervals (ATMOS 41, USA). Fig. 1 shows the maximum, minimum and mean monthly temperatures in two seasons.

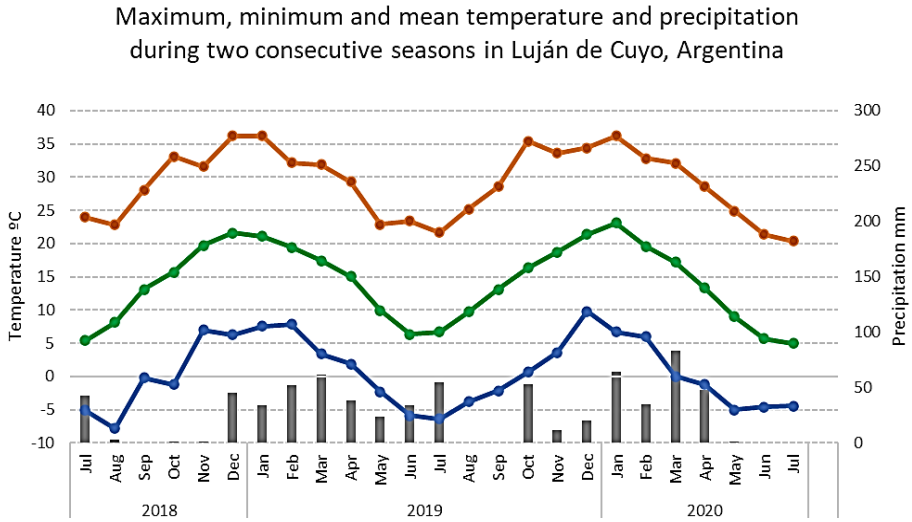

Figure 1. Maximum, minimum and medium monthly temperature and precipitation during two consecutive seasons (Luján de Cuyo-Argentina).

Clone 7 is one of three FPS (FPS: Foundation Plant Services) selections (FPS 07, 08, 11) that were taken from the same single vine source: Concannon R34 V2. C.J. Alley made the selection of this material when he headed the Foundation Plant Services at Davis in 1965. Clone 15, corresponds to the French certified selection *Cabernet Sauvingon* clones *15* (ENTAV-INRA ® 15) and its wines are fruity aromatic, easy to drink. Clone 169 was registered by ENTAV-INRA® as an Authorized *Cabernet Sauvignon clones* 169. The Institut Français de la Vigne et du Vin (IFV) maintains the French national repository of accredited clones and has created the ENTAV-INRA. This clone is aromatic and has good tannins. Clone 685 Registered; Authorized French clone *Cabernet Sauvignon* 685, from ENTAV in France has been patented.

The training system was Guyot with 31 buds per plant. During the growing season (September-April), canopy management practices, such as vertical positioning of shoots were carried out according to company practices. The amount of irrigation water applied was the same for the different clones evaluated. Harvest and sample extraction were carried out on the same day. All vines were pruned during the winter season (June-August) leaving 31 buds per plant. In spring, no differences were observed among clones in the number of simple shoot or cluster All measurements were made on the same day according to Perrone et al., (2012).

Leaf analyses

All measurements were performed on healthy, fully expanded leaves that were exposed to direct sunlight.

Leaf water potential

Stem water potential was measured at midday using a pressure chamber (PMS, model 600, Oregon, USA) on fully expanded mature leaves exposed to direct solar radiation at least 1 h before measurement (Saurin et al., 2014) in one leaf per plant and 25 plants per clone. Leaves were covered aluminized plastic bag and closed immediately according to Araujo et al., (1999). The measurement was performed on one leaf on each side of the plant and 25 plants per clone on three different dates.

Stomatal conductance

Stomatal conductance was measured using a Decagon Devices porometer, (model SC-1 Leaf Porometer. Made in Washington, USA) from the 8^{th} to the 10^{th} node from the top (Medrano et al., 2002). The measurement was performed on one leaf on each side of the plant and 25 plants per clone on three different dates (91, 113 and 153 days after flowering in season 1 and 95, 107 and 150 days after flowering in season 2).

Chlorophyll (Chl)

Gas exchange and Chlorophyll content were repeatedly measured on the same leaves (Schaper & Chacko, 1991) with SPAD Konica minolta, (model 502 DL, made USA). Leaf Chlorophyll contents is a key variable for predicting grapevine performance. The measurement was performed on one leaf on each side of the plant and on 25 plants per clone on three different dates.

Leaf area

At harvest, all leaves were removed from the plant for quantified total leaf area, lateral shoot leaf area, and principal shoot leaf area employing LICOR® Area meter portable (LI3000A-USA). For each evaluated clone, 25 plants were measured.

Potentially exposed foliage surface area

Potentially exposed foliage surface area an index was realized according Carbonneau et al, (2004), based on (i) a section across the canopy, (ii) the shadows cast by adjacent rows (in the case of divided canopies, foliage walls), (iii) the foliage discontinuities along the row, and (iv) the photosynthetic potential in different zones of the canopy concerning the age and position of the leaf inside the canopy. The measurement was performed on 25 plants per clone.

Yield components

Yield components were measured in five vines per clone, selected within each experimental unit. The number of grape clusters, berry count per cluster, berry weight, and fruit weight per vine were determined at harvest. In addition, the fertility index was calculated as the ratio of bunches per shoot.

Polyphenol concentration

Berry samples

At harvest time, 200 berries per plant were collected from each of the 5 vines per replicate to determine their chemical (Gadallah, 1996) and physical composition (berry weight, sugar concentration, pH, anthocyanin and phenolic compound concentrations). To determine production parameters, 5 plants per replicate were harvested, and the following were determined: kilograms per plant, number of bunches, bunch weight, and number of berries per bunch.

Extraction

To assess anthocyanin and phenolic concentrations, extracts were made according to Revilla et al., (1998), with minor modifications. Grape berry skins were crushed and macerated in darkness with 5 mL of methanol:chlorhydric acid solution 99:1 v/v, during 24 hours. Two millilitres of skin extracts (diluted 1:5 with HCl 0.1 N) per experimental unit was filtered through a 0.45 μm pore size nylon membrane, and then 50 μL.

Absorbance 280 and 520 nm

The resulting extract was diluted 100-fold in methanol and filtered. Subsequently, the total anthocyanin concentration and the total polyphenolic index were determined by measuring absorbance at 520 nm and 280 nm, respectively, using a spectrophotometer (Uvikon 922, Kontron Instruments, Milan, Italy) with a 1 cm path-length cuvette. Results were expressed in absorbance units.

Anthocyanin Composition and Quantitative Profile

The extract was injected in the HPLC-DAD system. The chromatographic system employed for wine anthocyanin identification and quantification was a Perkin-Elmer (Series 20 USA) high-performance liquid chromatograph equipped with a diode array detector, a quaternary pump, and an auto sampler (HPLC-DAD; PerkinElmer, Shelton, CT). Separation was performed on a reversed-phase Chromolith Performance C18 column (100 mm × 4.6 mm I.D., 2 μm; Merck, Darmstadt, Germany) with a Chromolith guard cartridge (10 mm × 4.6 mm) at 25 °C. A gradient consisting of solvent A (water/formic acid, 90:10, v/v) and solvent B (acetonitrile) was applied at a flow rate of 1.1 mL min^{-1} from 0 to 22 min and 1.5 mL min^{-1} from 22 to 35 min as follows: 96–85% A and 4–15% B from 0 to 12 min, 85–85% A and 15–15% B from 12 to 22 min, 85–70% A and 15–30% B from 22 to 35 min; followed by a final wash with 100% methanol and re-equilibration of the column. Diode array detection was performed from 210 to 600 nm, and the quantification was carried out by peak area measurements at 520 nm. Anthocyanin amount was expressed by using malvidin-3-glucoside chloride as standard for a calibration curve ($R^2 = 0.99$). Identification and confirmation of anthocyanin pigments were performed by HPLC-DAD/ESI-MS as described by Blanco-Vega et al. (2011).

Statistical analysis

The experimental unit was the vine and 30 vines per clone were used for statistical analysis. The data obtained in this study were subjected to analysis of variance (ANOVA) using the statistical software XLSTAT, with a significance level of $p = 0.05$ adopted to identify statistically meaningful differences among treatments. Multiple comparisons between means were performed using Fisher's test, ensuring a robust evaluation of specific differences among the evaluated clones. Additionally, a principal component analysis (PCA) was conducted to identify patterns of correlation and to group variables according to their relative contribution to the observed variability. All statistical procedures and corresponding calculations were carried out entirely using the XLSTAT package, ensuring the consistency, reliability, and reproducibility of the results obtained (Addinsoft, 2025).

RESULTS AND DISCUSSION

There were no significant differences among clones in stem water potential (Fig. 2, a, b). It is worth noting that all clones were grafted onto the 1103 Paulsen rootstock, which is characterized by its high water absorption and transport capacity.

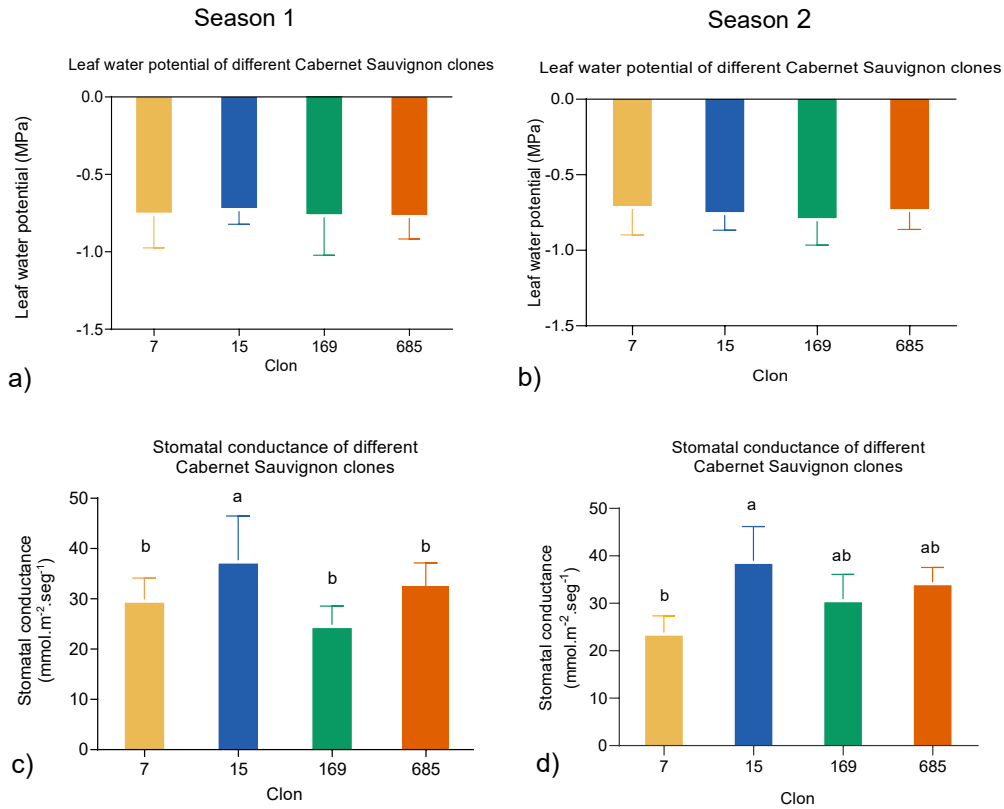

Figure 2. Leaf water potential and stomatal conductance of different clones of Cabernet Sauvignon during two consecutive seasons. Means affected by the same letter are not significantly different at $p \leq 0.05$. ns: no statistically significant difference.

To compare clonal performance of different clones, water stress was evaluated during the two seasons of highest evaporative demand, as vine water status is strongly related to grape quality (Ojeda et al., 2002). Significant differences in stomatal conductance were observed among clones (Fig. 2, c, d). The results suggest the existence of distinct adaptive strategies regarding stomatal regulation. Clones with higher stomatal conductance may have greater photosynthetic capacity under optimal conditions. However, they may also be more sensitive to water shortages, losing water more rapidly affecting the plant's water status, consequently impacting leaf and berry growth. Conversely, clones with low stomatal conductance may prioritize water use and be better suited to areas with low water availability and high temperatures. This trait, known as 'water use efficiency (WUE)', is a desirable characteristic in areas with water scarcity or during dry years. Clonal variability contributes to the differential regulation of water status and, consequently, the biosynthesis of polyphenols and stress-related metabolites, which confer a qualitative advantage in semi-arid climatic conditions.

Clone 7 consistently showed the lowest conductance during two consecutive seasons. In contrast, clone 15 presented the highest stomatal conductance among the four clones. Together with stomatal conductance, temperature is measured. In the season 1, the temperature at the time of measurement was 27.88 °C for 91 DAF (days after flowering), 28.84 °C for 113 DAF and 27.69 °C for 143 DAF (Table 1). All clones showed the lowest stomatal conductance value at 27.69 °C and the highest at 28.84 °C except clone 169 which showed the lowest value. Temperatures at the time of measurement between season 1 and 2 were similar (Table 1). The leaf temperature indicates reduced water loss through transpiration and, consequently, an increase in temperature. This temperature increase could be affecting the synthesis of secondary metabolites and, subsequently, the quality of the grapes.

Table 1. Stomatal conductance and temperature of different Cabernet Sauvignon clones at different days after flowering

	Clon	DAF	Stomatal conductance ($\mu moles.m^{-2}.s^{-1}$)	Temperature °C
Season 1	7	91	16.64 ± 2.92 c	27.4
	15	91	26.13 ± 2.92 c	29.52
	169	91	20.01 ± 3.19 c	28.6
	685	91	19.81 ± 2.92 c	27.62
	7	113	48.01 ± 2.92 a	29.34
	15	113	48.38 ± 3.02 a	27.9
	169	113	34.52 ± 2.92 b	28.52
	685	113	50.87 ± 3.02 a	29.62
	7	143	25.31 ± 2.92 c	26.84
	15	143	36.87 ± 2.92 b	28.83
	169	143	24.97 ± 2.92 c	27.52
	685	143	25.41 ± 2.92 c	27.57
Season 2	7	95	18.24 ± 2.12 c	29.3
	15	95	28.26 ± 1.92 c	30.25
	169	95	22.01 ± 1.91 c	28.8
	685	95	21.81 ± 3.01 c	28.6
	7	107	48.01 ± 2.18 a	28.4
	15	107	48.38 ± 3.02 a	28.2
	169	107	36.52 ± 2.12 b	29.25
	685	107	47.71 ± 3.02 a	29.02
	7	150	27.31 ± 3.02 c	27.84
	15	150	38.67 ± 2.82 b	28.31
	169	150	26.97 ± 3.04 c	29.25
	685	150	27.41 ± 2.99 c	29.62

In this study, chlorophyll content was higher in clone 7 than other clones. In clone 15, chlorophyll showed a decrease of 19% compared to clone 7 during two seasons. In general, chlorophyll content in each clone was similar between seasons (data not shown).

Fig. 3 illustrates the total vegetative growth of different clones revealing significant differences in canopy growth (total (a and b) and lateral shoot area (c and d)). Increased leaf development can be associated with higher chlorophyll content, stomatal conductance, net assimilation, and accumulation of sugars and other compounds in the berry, which may not always favor ripening. Excessive vegetative growth increases shading of the grapes, leading to competition and resulting in lower grape quality (Ferrer-Gallego et al., 2024; Perera-Castro & Hernández-Montes, 2025).

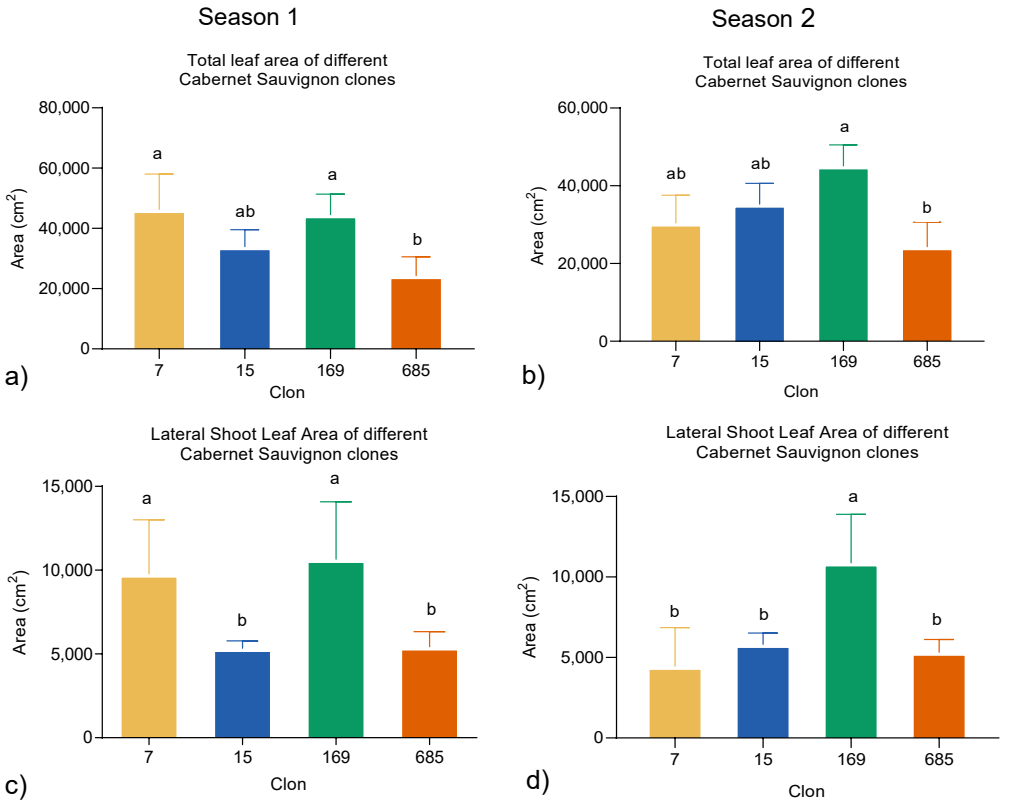

Figure 3. Total and lateral shoot leaf area of different clones of Cabernet Sauvignon during two consecutive seasons. Means affected by the same letter are not significantly different at $p \leq 0.05$.

Furthermore, very dense foliage increases susceptibility to fungal diseases if the canopy microclimate is not properly managed (Tivoli et al., 2013; Kraus et al., 2018). Clone 685 had the lowest total leaf area of the four clones in both seasons studied. The other three clones showed similar behaviour, with clone 169 tending to produce the highest total leaf area (Fig. 3 a and b). This superior total leaf area in clone 169 was due to greater growth of secondary shoots (Fig. 3 c and d). This growth may have the disadvantage of excessive shading of basal buds, affecting bud fertility, diminishing the colour of red grapes, increasing the incidence of disease, and reducing the efficiency of applying phytosanitary products in the area of greatest leaf density. In addition, clones that developed greater secondary leaf area may require more intensive pruning or defoliation

practices to maintain an adequate balance between source and sink. From an oenological perspective, this reduces the quality of total anthocyanins and characteristic aromas of the variety (Lu et al., 2021; Nan et al., 2024).

Table 2 shows the yield components of the clones across two consecutive seasons. Clone 169 was the most productive, while clone 15 showed the lowest yield. The differences in yields were caused by the variation in bunch weight given by the number of berries and not by the unit weight of each berry. The number of bunches per plant showed no statistically significant differences.

Table 2 show °Brix or pH during two consecutive seasons. During the first seasons, clones 15, 169, and 685 showed higher soluble solids (24.9, 25.5, and 25.3 °Brix, respectively) compared to clone 7 (23.6 °Brix). In contrast, in the second seasons, no statistically significant differences were recorded among clones, with soluble solids ranging from 23.8 to 24.7 °Brix. These results suggest that sugar accumulation can be more influenced by climatic condition than by clonal genotype.

Table 2. Grapevine production and plant leaf measurement

Season	Clon	Yield ($kg.plant^{-1}$)	Nº of cluster per plant	Cluster weight (g)	Nº berries per cluster	Berry weight (g)	ºBrix (soluble solids)	pH
Season 1	7	4.06 ± 0.83ab	47.5 ± 8	85.59 ± 11.3a	65.03 ± 6.51a	1.32 ± 0.17	23.6 ± 1.14a	4.16 ± 0.2
	15	2.71 ± 0.66b	48 ± 9.8	56.55 ± 9.35b	47.72 ± 9.09b	1.19 ± 0.10	24.9a ± 0.55b	4.13 ± 0.3
	169	4.73 ± 1.13a	55 ± 11	85.88 ± 15.47a	64.64 ± 12.69a	1.34 ± 0.17	25.5 ± 1.22b	4.04 ± 0.3
	685	2.98 ± 1.38b	48.9 ± 15	60.98 ± 17.35b	47.41 ± 10.51b	1.28 ± 0.14	25.3 ± 0.67b	4.06 ± 0.2
Season 2	7	4.25 ± 0.63a	46.5 ± 9	91.33 ± 16.65a	68.74 ± 5.19a	1.51 ± 0.21	24.7 ± 0.17	3.87 ± 0.4
	15	2.92 ± 0.62b	47.6 ± 8.8	61.32 ± 9.06b	51.67 ± 8.64b	1.30 ± 0.17	24.04 ± 0.2	4.01 ± 0.3
	169	4.83 ± 0.82a	54.3 ± 10.5	88.93 ± 12.95a	67.16 ± 13.94a	1.38 ± 0.12	23.82 ± 0.9	3.70 ± 0.3
	685	2.96 ± 1.26b	48.9 ± 13.6	60.6 ± 13.77b	47.42 ± 9.74b	1.28 ± 0.10	24.4 ± 1.2	3.81 ± 0.4

Significant level, data were analyzed with one-way ANOVA, significant at $p \leq 0.05$.

Must pH did not show significant differences between clones in either of the two seasons evaluated. Values ranged between 4.04 and 4.16 in the first year, and between 3.70 and 4.01 in the second, remaining within expected ranges for *Cabernet Sauvignon* in semi-arid regions. The stability of this parameter reinforces the idea that, although clones may differ in physiological and phenolic traits, fruit acidity is not markedly affected by clonal material under these growing conditions. No evidence was found that clonal variability in *Cabernet Sauvignon* in this study affects or modifies pH.

In addition to the viticultural traits, the leaf area to fruit weight ratio, exposed leaf area and fertility index were also evaluated. While the differences were not statistically significant, the data shown a reliable trend in the behavior of each clone (Table 3). Clone 7 consistently exhibited the highest fertility index across both seasons (1.98 ± 0.44 in season 1 and 2.07 ± 0.13 in season 2), indicating a different reproductive capacity in relation to the other clones. This high fertility, combined with the highest leaf area and fruit fresh weight ratio, particularly in the second year (1.4 ± 0.54 $m^2\ kg^{-1}$), suggests that clone 7 maintains a favourable source–sink balance, ensuring adequate photosynthesis support for fruit development and quality. In contrast, clone 169 showed the lowest fertility, especially in Year 2 (1.38 ± 0.93), together with a low leaf area and fruit fresh weight ratio (0.94 ± 0.16 $m^2\ kg^{-1}$ in season 1), indicating a tighter source-sink ratio that could limit sugar accumulation and phenolic maturation under higher fruit loads. Clones 15 and 685 presented intermediate fertility and leaf area. The exposed leaf area showed different trends depending on the clone. Clone 15 had the largest exposed leaf area (2.19 and 2.37 m^2 in the first and second seasons) along with clone 169 (2.13 and 2.42 m^2), suggesting that the canopy is sufficient for good fruit ripening. However, clone 685 showed the smallest exposed leaf area (1.96–1.97 m^2), indicating that dense or more clustered canopy could reduce photosynthetic efficiency and affect fruit quality under certain conditions. Several authors have proposed different values for adequate fruit ripening. These values can vary from 0.768 to 1.2 $m^2\ kg^{-1}$ of fruit (Kliewer & Dokoozlian, 2005; Beslic et al., 2010). In our study, clones 15 and 169 showed a leaf area to fruit ratio of 1–1.2 $m^2\ kg^{-1}$ (Table 3), suggesting a balanced relation between vegetative growth and yield, which favors the attainment of optimal soluble solids, berry weight, and coloration at harvest.

Table 3. Viticultural traits of grapevine clones 7, 15, 169, and 685: fertility index (clusters per shoot), leaf area-to-fruit weight ratio ($m^2\ kg^{-1}$), and exposed leaf area measured over two consecutive easons

Season	Clone	Fertility index (cluster.shoot^{-1})	Leaf area and fruit fresh weight ratio ($m^2.kg^{-1}$)	Exposed leaf area ($m^2.m^{-2}$)
1	7	1.98 ± 0.44	1.2 ± 0.64	2.02 ± 0.35
	15	1.42 ± 0.15	1.15 ± 0.29	2.19 ± 0.23
	169	1.68 ± 0.31	0.94 ± 0.16	2.13 ± 0.44
	685	1.43 ± 0.39	1.11 ± 0.8	1.97 ± 0.46
2	7	2.07 ± 0.13	1.4 ± 0.54	2.35 ± 0.52
	15	1.55 ± 0.22	1.25 ± 0.37	2.37 ± 0.75
	169	1.38 ± 0.93	1.07 ± 0.18	2.41 ± 0.82
	685	1.42 ± 0.32	1.11 ± 0.6	1.96 ± 0.47

Significant level; data were analyzed with one-way ANOVA, significant at $p \leq 0.05$.

This was coincident with our results because clones 7 and 169 showed the highest yields, cluster weight and number of berries per cluster. Even though, total leaf area presented differences, those clones showed highest values but more lateral shoot area than clones 15 and 685 in 2020. This difference could be explained by the ability to produce clusters of greater weight. The relations between the kilograms of grapes produced and the weight or leaf area are widely used parameters to characterize plant balance and

an important tool for canopy management (Jackson & Lombard, 1993; Kliewer & Dokoozlian, 2005).

An indicator of balanced vines is the fruit weight:pruning weight ratio. This ratio has been widely studied and is recommended to range between 5 and 10. This range represents balanced vines that will produce quality wines (Bravdo et al., 1985; Reynolds et al., 1995; Smart & Robinson, 1991). In this study, the values found for exposed leaf area ranged between 1.96 and 2.41 m^2. Clone 7 had the highest reproductive capacity and leaf area, optimizing the source-destination ratio.

The number of clusters per shoot is called the fertility index. Clone 169 had lower fertility index and a larger exposed leaf area. Clones with low bud fertility are clones that exhibit low production with the same bud load as other clones. This knowledge is crucial when determining the number of buds to leave during winter pruning. It also provides insight into how to manage the canopy during the summer to maximize yield and quality.

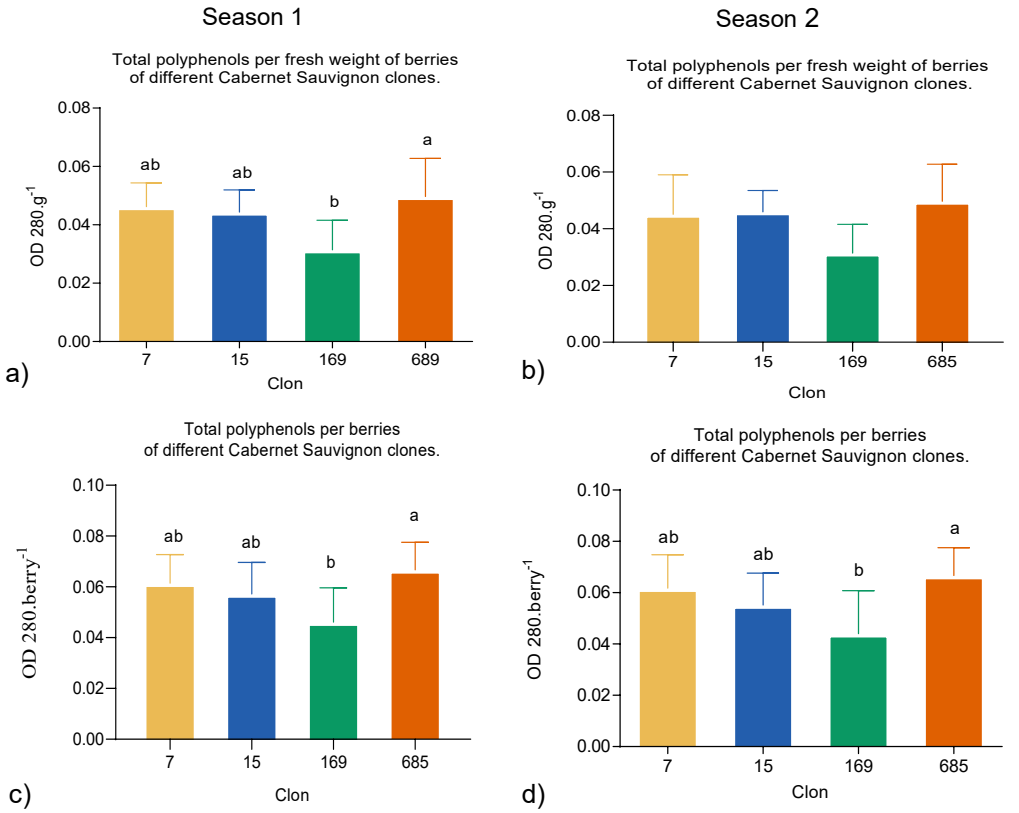

Figure 4. Total polyphenols per fresh weight and berries of different clones of Cabernet Sauvignon during two consecutive seasons. Means affected by the same letter are not significantly different at $p \leq 0.05$.

In grapes, the polyphenol concentration per gram of fresh berry was determined (Fig. 4, (a–d). This parameter is indicative of the berry's phenolic content, which is closely related to wine color and astringency. Significant variations was found among

clones suggesting that genetic characteristics influenced not only plant growth and physiology but also the accumulation of secondary metabolites. A higher polyphenol concentration per unit weight may be due to better synthesis or less dilution due to smaller berry size. Both mechanisms ultimately lead to higher phenolic intensity in the must and wines. In either case, this is a desirable oenological characteristic, especially in the production of wines with high aging potential or tannic structure. This quantification allows distinguishing between the effect of concentration (quantity of polyphenols per unit weight) and the effect of total synthesis (quantity of polyphenols produced in each berry) (Ojeda et al., 2002). Clone 169 showed the lowest total phenol content per berry and per gram of berries in both seasons. This could be explained by its shaded canopy resulting from the high leaf area of the secondary shoots. This information is essential for winemakers interested in optimizing the phenolic profile of wine, as well as for winegrowers who wish to select clones based on the desired final product.

Table 4 presents the anthocyanin profile of grapes from different clones. Total anthocyanin concentration expressed as mg kg^{-1} skin, mg $berry^{-1}$, and mg g^{-1} fresh berry weight, revealed that clone 685 accumulated the highest levels of the main grape color compounds, including malvidin-3-glucoside (1,065.35 mg kg^{-1} skin, $p \leq 0.01$), petunidin-3-(6"-acetyl) glucoside (39.05 mg kg^{-1} skin, $p \leq 0.05$), and coumaroylated derivatives such as trans-malvidin-3-(6"-p-coumaroyl) glucoside (127.92 mg kg^{-1} skin, $p \leq 0.05$). These results indicate a higher biosynthetic capacity of clone 685, which could be reflected in wines with greater color intensity. Interestingly, this pattern does not follow the vegetative growth trend. Clone 169 exhibited the largest total leaf area and vigorous secondary shoot development, which theoretically should enhance carbon assimilation and anthocyanin synthesis. However, its anthocyanin accumulation was intermediate, indicating that excessive vegetative growth may have resulted in a shaded canopy, reducing anthocyanin synthesis. Furthermore, competition for assimilates between vegetative and reproductive sinks can reduce carbon allocation to the berry's secondary metabolism (Poni et al., 2006; Intrigliolo & Castel, 2010).

In contrast, clones 7, 15, and 169 showed intermediate or lower concentrations: clone 15 tended towards intermediate values, clone 169 towards intermediate-low levels, and clone 7 showed the lowest accumulation of these colored compounds. These trends confirm the importance of using specific clones to achieve a specific product. In contrast, clone 685, with a smaller leaf area and moderate vigor, may have maintained a more balanced source-sink relations, favoring canopy illumination and the partitioning of photoassimilates towards berry phenolic biosynthesis (Torregrosa et al., 2021).

Similar results were reported in Malbec, where genetic variability generated significant variations in the synthesis of secondary metabolites (Muñoz et al., 2014). When expressing anthocyanins per berry and per unit of fresh weight, clone 685 again showed higher amounts of delphinidin-3-(6"-p-coumaroyl) glucoside and malvidin-3-(6"-acetyl) glucoside, highlighting its oenological potential. While clone 685 showed the highest concentrations in the anthocyanin profile, it produced the lowest yields per plant without affecting berry size.

Table 4. Individual anthocyanins quantified in different clones of Cabernet Sauvignon berry skins from Luján de Cuyo, Mendoza, Argentina

Clone	7		15		169		685		Sig
	Mean	± SD	Mean	± SD	Mean	± SD	Mean	± SD	
mg. kg^{-1} of skin									
delphinidin-3-glucoside	115.8	± 61.6	155.95	± 66.2	118.81	± 30.42	175.47	± 53.02	ns
cyanidin-3-glucoside	24	± 11.3	31.52	± 12.81	24.86	± 5.52	30.08	± 7.11	ns
petunidin-3-glucoside	101.1	± 42.6	117.79	± 46.66	95.24	± 20.98	142.59	± 38.37	ns
peonidin-3-glucoside	98.8	± 51.9	97.33	± 33.75	89.02	± 21.73	120.78	± 28.33	ns
malvidin-3-glucoside	**787ab**	± **219.3**	**728.4ab**	± **233.6**	**666.83a**	± **110.11**	**1065.35b**	± **183.38**	**
delphinidin-3-(6′′-acetyl)glucoside	26.87	± 4.76	28.13	± 5.06	26.52	± 2.34	35.02	± 10.23	ns
cyanidin-3-(6′′-acetyl)glucoside	**22.45ab**	± **3.38**	**18.63a**	± **3.02**	**20a**	± **1.22**	**26.79b**	± **4.51**	*
petunidin-3-(6′′-acetyl)glucoside	**29.08a**	± **3.97**	**28.01a**	± **4.62**	**26.79a**	± **3.22**	**39.05b**	± **11.69**	**
peonidin-3-(6′′-acetyl)glucoside	**41.27ab**	± **8.84**	**29.58a**	± **4.74**	**33.26ab**	± **3.49**	**43.44b**	± **7.17**	*
malvidin-3-(6′′acetyl)glucoside	**231.8**	± **62.6**	**18.13**	± **3.72**	**19.1**	± **4.49**	**34.16**	± **14.72**	**
delphinidin-3-(6′′-p-coumaroyl)glucoside	**30.42ab**	± **5.99**	**24.52a**	± **5.15**	**26.64a**	± **3.26**	**36.1b**	± **10.04**	***
cyanidin-3-(6′′p-coumaroyl)glucoside	**13.75b**	± **2.74**	**10.79a**	± **1.7**	**11.91ab**	± **1.33**	**14.81c**	± **3.06**	***
petunidin-3-(6′′-p-coumaroyl)glucoside	**15.4ab**	± **2.8**	**13.42a**	± **2.55**	**12.42a**	± **0.98**	**18.97b**	± **2.88**	*
peonidin-3-(6′′-p-coumaroyl)glucoside	**24.2ab**	± **6.7**	**21.53a**	± **4.13**	**20.95a**	± **3.51**	**29.75b**	± **5.1**	**
malvidin-3-(6′′-p-coumaroyl)glucoside *trans*	**90.6a**	± **16.1**	**81.24a**	± **22.49**	**73.19a**	± **11.13**	**127.92b**	± **12.8**	*
malvidin-3-(6′′-p-coumaroyl)glucoside *cis*	**19.9ab**	± 3.21	**17.8a**	± 3.88	**17.7a**	± 1.79	**24.6b**	± 3.55	**
malvidin-3-(6′′-caffeoyl)glucoside	**21.41c**	± **2.68**	**15.34a**	± **4.2**	**17.32ab**	± **1.4**	**24.22c**	± **6.34**	**
mg.$berry^{-1}$									
delphinidin-3-glucoside	**3.18a**	**± 2.15**	**6.19b**	**± 1.83**	**4.84ab**	**± 1.22**	**5.88b**	**± 1.51**	***
cyanidin-3-glucoside	**0.67a**	**± 0.43**	**1.25b**	**± 0.36**	**1.01b**	**± 0.21**	**1ab**	**± 0.15**	***
petunidin-3-glucoside	**2.81a**	**± 1.75**	**4.69b**	**± 1.24**	**3.88ab**	**± 0.82**	**4.78b**	**± 1.07**	***
peonidin-3-glucoside	2.72	± 1.84	3.9	± 0.9	3.62	± 0.84	4.06	± 0.76	ns
malvidin-3-glucoside	**22.31a**	± **12.94**	**29.22ab**	± **5.87**	**27.12a**	± **4.22**	**36.09b**	± **6.42**	***
delphinidin-3-(6′′-acetyl)glucoside	0.77	± 0.44	1.15	± 0.17	1.08	± 0.11	1.15	± 0.25	ns
cyanidin-3-(6′′-acetyl)glucoside	0.65	± 0.37	0.76	± 0.08	0.81	± 0.06	0.9	± 0.06	ns
petunidin-3-(6′′-acetyl)glucoside	0.84	± 0.49	1.15	± 0.2	1.1	± 0.17	1.28	± 0.28	ns
peonidin-3-(6′′-acetyl)glucoside	1.2	± 0.75	1.01	± 0.26	1.09	± 0.18	1.19	± 0.2	ns

Table 4 (continued)

malvidin-3-(6´´acetyl)glucoside	6.89	± 4.71	1.21	± 0.19	1.36	± 0.18	1.46	± 0.18	ns
delphinidin-3-(6´´-p-coumaroyl)glucoside	0.88	± 0.53	1.01	± 0.26	1.09	± 0.18	1.19	± 0.2	ns
cyanidin-3-(6´´p-coumaroyl)glucoside	0.39	± 0.22	0.44	± 0.02	0.48	± 0.04	0.49	± 0.05	ns
petunidin-3-(6´´-p-coumaroyl)glucoside	0.44	± 0.25	0.55	± 0.05	0.51	± 0.03	0.64	± 0.05	ns
peonidin-3-(6´´-p-coumaroyl)glucoside	0.69	± 0.4	0.88	± 0.13	0.85	± 0.14	1	± 0.09	ns
malvidin-3-(6´´-p-coumaroyl)glucoside trans	**2.63a**	± **1.58**	**3.29a**	± **0.73**	**2.98a**	± **0.48**	**4.33b**	± **0.47**	***
malvidin-3-(6´´-p-coumaroyl)glucoside cis	0.57	± 0.33	3.29	± 0.73	2.98	± 0.48	4.33	± 0.47	ns
malvidin-3-(6´´-caffeoyl)glucoside	0.62	± 0.35	0.72	± 0.1	0.72	± 0.08	0.82	± 0.04	ns
$mg.g^{-1}$ of fresh berry weight									
delphinidin-3-glucoside	29.35	± 9.3	50.11	± 14.88	35.32	± 11.13	43.61	± 13.59	ns
cyanidin-3-glucoside	**6.17a**	**± 1.63**	**10.17b**	**± 2.93**	**7.38a**	**± 2.04**	**7.44a**	**± 1.77**	***
petunidin-3-glucoside	26.02	± 5.5	37.94	± 10	28.26	± 7.61	35.48	± 10.2	ns
peonidin-3-glucoside	25.08	± 8.01	31.52	± 7	26.5	± 7.91	30.19	± 8.64	ns
malvidin-3-glucoside	207.45	± 25.92	236.46	± 45.3	197.3	± 41.3	266.6	± 63.6	ns
delphinidin-3-(6´´-acetyl)glucoside	7.17	± 0.61	9.27	± 0.81	7.81	± 0.79	8.59	± 2.25	ns
cyanidin-3-(6´´-acetyl)glucoside	6.06	± 0.98	6.15	± 0.47	5.9	± 0.61	6.64	± 1.22	ns
petunidin-3-(6´´-acetyl)glucoside	7.88	± 1.41	9.26	± 1.07	7.88	± 0.82	9.58	± 2.66	ns
peonidin-3-(6´´-acetyl)glucoside	11.21	± 2.91	9.81	± 1.28	9.77	± 0.82	10.72	± 1.4	ns
malvidin-3-(6´´acetyl)glucoside	65.26	± 26.72	60.64	± 14.34	54.06	± 12.76	70.98	± 19.64	ns
delphinidin-3-(6´´-p-coumaroyl)glucoside	8.27	± 2.01	8.17	± 1.84	7.84	± 0.89	8.87	± 2.34	
cyanidin-3-(6´´p-coumaroyl)glucoside	3.68	± 0.51	3.57	± 0.3	3.53	± 0.6	3.67	± 0.82	ns
petunidin-3-(6´´-p-coumaroyl)glucoside	**4.13ab**	**± 0.56**	**4.42b**	**± 0.36**	**3.67a**	**± 0.51**	**4.7b**	**± 0.78**	***
malvidin-3-(6´´-caffeoyl)glucoside	5.77	± 0.77	5.04	± 0.96	5.11	± 0.56	6	± 1.68	ns
peonidin-3-(6´´-p-coumaroyl)glucoside	6.41	± 0.99	7.09	± 0.67	6.21	± 1.34	7.10	± 1.51	ns
malvidin-3-(6´´-p-coumaroyl)glucoside trans	**32.84a**	**± 6.62**	**32.91ab**	**± 7.25**	**29.83a**	**± 4.79**	**31.81b**	**± 4.35**	**
malvidin-3-(6´´-p-coumaroyl)glucoside cis	5.39	± 1.06	5.86	± 0.75	5.22	± 0.67	6.08	± 0.81	ns

Significant level; data were analyzed with one-way ANOVA, *,**,***; ns: significant at $p \leq 0.01$, $p \leq 0.05$, $p \leq 0.1$ or not significant, respectively. When differences among treatments were significant, the LSD method was used to separate the means; different letters represent different means.

Furthermore, the clone 685 achieved higher sugar concentrations at harvest, suggesting earlier phenolic ripening compared to the other clones. This combination of traits could be very advantageous in cold climates, while it could be detrimental in warm climates where later rather than earlier ripening is desired. To visualize the overall variability of the clones, a principal components analysis was performedThis Principal Component Analysis (PCA) explained 91% of the total variability among clones (Fig. 5). The first component explained 62% of the variability among clones and was associated with yield, productivity index, water potential, and crop load. The second component explained 30.3% and consisted of berry pH, weight, color intensity, anthocyanin concentration stomatal conductance, and pruning weight. These two components explained 92% of the variability among clones. From this analysis, the clones can be divided into four groups: (i) low productivity with intermediate anthocyanin concentration (clone 15), (ii) low productivity with high anthocyanin concentration (clone 685), (iii) high productivity with intermediate anthocyanin concentration (clone 169), and (iv) the highest productivity with low anthocyanin concentration (clone 7). These results are coincident with previous work showing clone-specific phenolic profiles in Malbec and their impact on wine color and sensory attributes (Urvieta et al., 2021; Rafique et al. 2023c, 2025b).

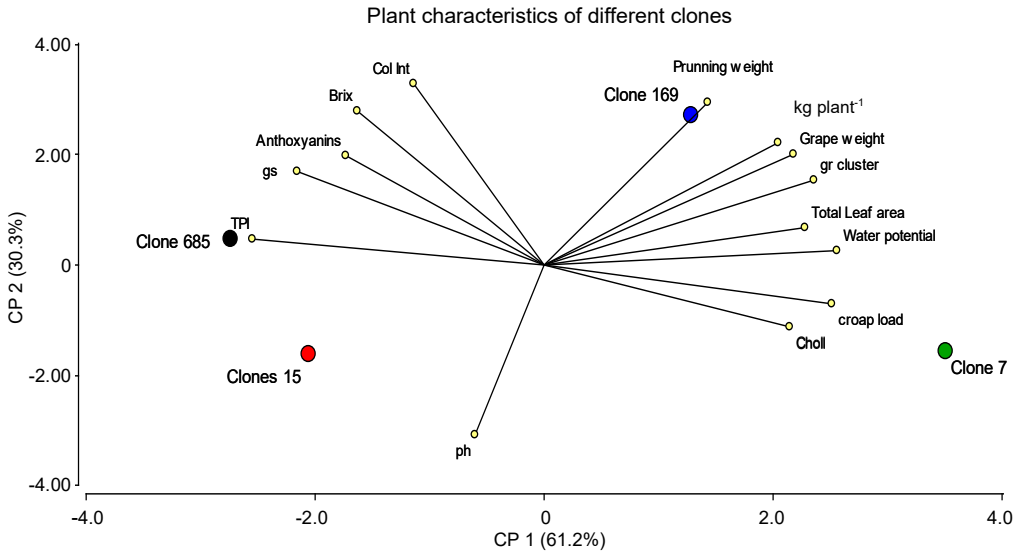

Figure 5. Principal components analysis of plant characteristics of different clones of Cabernet Sauvignon grown under the same conditions during two seasons.

Taken together, these results highlight that clonal differences in anthocyanin accumulation are not determined solely by yield or leaf area, but rather by the interaction between canopy architecture, water use efficiency, and metabolic plasticity. Clone 685, therefore, represents a genotype with high qualitative efficiency, whereas clone 169, despite its vigor, appears to develop an overly dense canopy that affects secondary metabolism and, consequently, the oenological potential. Increased metabolic efficiency could reflect the differential activation of secondary metabolism in response to drought, particularly the biosynthesis of phenolic compounds and stilbenes that act as antioxidants

and stress mitigators (Daldoul et al., 2024; Hanzouli et al., 2025). These responses are consistent with findings in wild and cultivated grapevine genotypes, where drought and salinity tolerance were associated with greater accumulation of phenolic compounds and modulation of antioxidant pathways (Daldoul et al., 2023). These results reinforce the importance of leveraging clonal and intraspecific variability in Vitis vinifera to mitigate the impacts of climate change by selecting clones with superior physiological and metabolic adaptation potential.

CONCLUSIONS

Diverse clones of *Cabernet Sauvignon* (7, 15, 169, 685) grown under the same semi-arid conditions during two consecutive seasons showed variable physiological behaviour, vegetative growth, yield, and berry composition. Although no differences were observed in stem water potential or stomatal conductance (Fig. 2). The results indicated distinct adaptation strategies among clones. Clones 7 and 169 achieved the highest productivity, although clone 7 showed lower phenolic content, while clone 685 consistently presented the highest concentrations of anthocyanins and polyphenols (Fig. 4 and Table 4) despite lower yields, highlighting its potential for premium wine production (Table 2). Clone 15 showed the lowest productivity with an intermediate berry composition.

From a viticultural and oenological perspective, these findings provide useful information for clone selection in semi-arid conditions. Clones such as 7 and 169 can be prioritized in vineyards seeking stable yields and higher production, while clone 685 could be recommended for vineyards focused on producing high-quality wines rich in phenolic compounds. The observed physiological differences, particularly in transpiration, leaf area, and phenolic compound accumulation, suggest that winegrowers can adapt pruning intensity, foliage management, and irrigation schedules according to each clone's growth pattern. Therefore, clonal variability represents not only a genetic resource for maintaining productivity under climatic stress but also a management tool for optimizing the balance between yield and quality in semi-arid viticulture. For high-quality wines in semi-arid regions, clone 685 appears to be the most appropriate to achieve this goal. However, clone 15 also showed good performance for quality wine production. If the objective is the production of young wines with lower tannin content, clones 169 and 7 would be the most suitable.

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