



VITICULTURE ORIGINAL RESEARCH ARTICLES

Phenolic and sensory profiles distinguish Malbec wines according to intra-vineyard soil effective depth across different vintages

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† In the memory of Federico Berli.

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ABSTRACT

High-elevation viticulture in Mendoza is increasingly recognised among the world's top wine regions. This unique terroir combines heterogeneous alluvial soils, intense solar ultraviolet-B (UV-B) radiation and cool night temperatures, creating distinct phenotypic expressions of *Vitis vinifera* L., particularly Malbec, Argentina's most important grapevine variety. This three-year study investigated intra-vineyard soil heterogeneity by evaluating the impact of contrasting soil profiles of shallow (SS) and deep (DS) soils on the qualitative and quantitative phenolic profiles, antioxidant capacity, and sensory attributes of Malbec wines. The experiment was carried out on a 1450 m a.s.l. vineyard selecting parcels with different effective soil depth (SS: 0–0.45 m; DS: 1–1.5 m) and physicochemical properties, but matching viticultural management and irrigation. Ripening occurred earlier in SS, and grapes were harvested at comparable °Brix across soil types; however, harvest °Brix varied by season. Winemaking was conducted in replicates using standardised procedures.

Two-way ANOVA revealed significant main effects of soil type and vintage, plus their interaction. While vintage effects were significant, SS consistently produced wines with higher dihydroxylated and non-acylated anthocyanins, as well as greater antioxidant capacity (ORAC) and total anthocyanin content in two of the three vintages. Low-molecular-weight polyphenols (LMWPs) such as polydatin (a stilbene), astilbin (a dihydroflavonol), and quercetin (a flavonol) were significantly higher in SS wines, whereas *p*-coumaric acid (a hydroxycinnamic acid) and (–)-epicatechin (a flavanol) predominated in DS wines. Sensory analysis revealed that expert tasters consistently distinguished and preferred SS wines, which were perceived as more acidic and astringent. In contrast, DS wines were characterised by sweeter flavours and jam, green pepper, leather, and earthy notes. The perception of mineral aroma did not differ between soil types.

These findings contribute to a better understanding of how soil profile influences Malbec wine composition and sensory descriptor expressions in a consistent manner, that is, under variable seasonal conditions, fundamental for terroir-driven wine production.

KEYWORDS: alluvial soils, anthocyanins, antioxidant capacity, low-molecular-weight polyphenols, Malbec, sensory analysis, *Vitis vinifera* L.

INTRODUCTION

The composition and sensory attributes of red wines result from the complex interplay among phenolic compounds, sugars, organic acids, and aromatic molecules present in grapes or produced during wine elaboration. Among these, phenolic compounds play a pivotal role due to their impact on colour, mouthfeel, and ageing potential, as well as their recognised nutraceutical properties (Buljeta *et al.*, 2023; Ribéreau-Gayon *et al.*, 2006). Their synthesis is genetically regulated but also modulated by environmental conditions (Berli *et al.*, 2011; Muñoz *et al.*, 2014; Downey *et al.*, 2006).

Phenolics encompass several classes, including phenolic acids (hydroxycinnamic and hydroxybenzoic acids), stilbenes (*trans*-resveratrol and polydatin), flavanols, flavonols, and anthocyanins, each contributing differently to wine quality (Berli *et al.*, 2011; Buljeta *et al.*, 2023). Phenolic acids participate in the formation of acylated anthocyanins, while stilbenes play a key defensive role against pathogens and abiotic stresses, enhancing the antioxidant capacity of wine (Ribéreau-Gayon *et al.*, 2006). Flavanols, the most abundant phenolics in grapes, tend to polymerise during ripening, reducing their extractability and affecting wine softness and astringency (Berli *et al.*, 2011; Fanzone *et al.*, 2012). Flavonols contribute to colour stabilisation through copigmentation, whereas anthocyanins define red wine colour intensity and hue, influenced by pH and specific hydroxylation and methoxylation patterns (Berli *et al.*, 2011; Gordillo *et al.*, 2012; Castillo-Muñoz *et al.*, 2009).

Environmental factors such as ultraviolet-B (UV-B) exposure and water availability significantly affect flavonoid biosynthesis, thereby modulating wine astringency, bitterness, and overall sensory quality (Koundouras, 2018; Berli *et al.*, 2015). At the regional scale, vintage effects often surpass soil-related influences on grape and wine composition (van Leeuwen *et al.*, 2004; Reynolds *et al.*, 2007; Priori *et al.*, 2019). However, at a more localised scale, soil variability emerges as a key driver of fruit quality, fostering growing interest in vineyard zoning and parcel-based vinification aimed at producing terroir-driven wines (Brillante *et al.*, 2016; Verdugo-Vásquez *et al.*, 2022; Sams *et al.*, 2022).

The Gualtallary region (Tupungato, Mendoza) is internationally recognised for producing high-quality Malbec wines, which exhibit elevated phenolic concentrations, attributed to high UV-B exposure, cool temperatures, and smaller berry size (Berli *et al.*, 2010; Berli *et al.*, 2015). These factors lead to concentrated metabolites with enhanced sensory and functional properties (Ojeda *et al.*, 2002; Berli *et al.*, 2008; Alonso *et al.*, 2016; Yu *et al.*, 2020).

Soil properties also influence sensory attributes such as minerality, a concept gaining traction in terroir-focused wines. While minerality is often associated with geological origin, its sensory and chemical bases remain under debate (Parr *et al.*, 2018; Maltman, 2008; Maltman, 2013; Goode, 2012). In Argentina, Malbec wines from shallow

soils have been described aromatically as more mineral than those from deeper profiles, although the specific compounds responsible are still unclear (Roig-Puscama *et al.*, 2025). Beyond aroma, mineral perception in the mouth has been linked to salinity, acidity, and astringency, suggesting a multisensory integration influenced by both composition and texture (Ballester *et al.*, 2013).

This study aims to investigate the effect of contrasting soil profiles (shallow *vs.* deep), located in the same vineyard, on the phenolic composition and sensory properties of Malbec wines over different vintages. The evaluation of wines elaborated under standardised winemaking conditions over three consecutive vintages aimed to determine if differences emerge and to provide new insights into soil-driven variability within a single vineyard. This kind of deep typification of contrasting soils inside a unique origin could help to understand their implication in wine characteristics and to highlight the importance of considering this point in the development of an integrated terroir concept perspective.

MATERIALS AND METHODS

1. Site characterisation

The study was conducted over three consecutive growing seasons (2016–2018) in a high-elevation commercial vineyard located in Gualtallary, Uco Valley region, Mendoza, Argentina (33° 23' S, 69° 15' W; 1450 m a.s.l.), using 23-year-old own-rooted Malbec vines. Mezzatesta *et al.* (2022) reported that the 2016 season was the coldest and rainiest of the three vintages under study, with accumulated precipitation from September to March of 775 mm, and maximum (T_{max}) and minimum (T_{min}) mean air temperatures of 21.4 °C and 9.3 °C, respectively. In contrast, data for the same period from the rest of the vintages were presented as follows, showing higher consistency with the average of the area: for 2017, rainfall = 289 mm, T_{max} = 24.0 °C, T_{min} = 9.3 °C; and for 2018: rainfall = 189 mm, T_{max} = 23.9 °C, T_{min} = 8.7 °C.

Soils of the region were formed on Quaternary deposits from alluvial fans with parent materials of volcanic and metamorphic lithologies (Polanski, 1963; Mehl & Zárate, 2012; Pepin *et al.*, 2013) that, after several phases and events, originated heterogeneous soil profiles, such as those considered in this study (Rubio *et al.*, 2019; Roig-Puscama *et al.*, 2021). At the Gualtallary area, they are characterised by variable top layer depth and the presence of carbonate accumulation that increased in areas closer to the “El Jaboncillo” and “El Peral” mountain ranges (Corona, 2019). Detailed information on site selection, soil classification, management practices, and vineyard experimental setup is available in Mezzatesta *et al.* (2022). Briefly, two contrasting soil types with an area of 0.15 ha each and located 30 m apart were selected within the same vineyard based on effective soil depth: deep soil (DS, 1.0–1.5 m) and shallow soil (SS, 0–0.45 m). Both soil types were studied up to 1.65 m depth and classified as sandy in texture. Soil pH ranged from 7.38 (DS) to 7.26 (SS)

and its main differences lied on: the topsoil depth, % of stones content (DS: 0 %; SS: 77 %), identified soil layers within the soil profile (DS: 3, SS: 6), Available Water Content (DS: 50.6 mm; SS: 12.6 mm), calcium carbonate content (DS: 0.23 %, SS: 1.84 %) and number of fine roots (< 1 mm): DS: 1011, SS: 4060; roots m⁻²). A split-plot design was implemented, with soil type as the main factor. For winemaking purposes, plots were selected randomly within each site to reach the quantity of grapes needed for vinification. The number of replicates per season was as follows: 2016 (n = 3), 2017 (n = 4), 2018 (n = 5).

2. Harvest and Vinification

Grapes were hand-harvested at 22–24 °Brix (comparable across soil types but differing between seasons) in 15 kg plastic boxes. Vinification followed standardised procedures as described by Urvieta *et al.* (2018). Grapes were destemmed, lightly crushed, and transferred to 20 L food-grade plastic fermenters.

Must parameters were recorded prior to fermentation: total soluble sugars (TSS) with a Pocket PAL-1 digital refractometer (Atago Co., Ltd., Tokyo, Japan), titratable acidity (TA) by titration with 0.1 N NaOH (endpoint pH 8.2), and pH using a calibrated portable pH meter. At crushing, 50 mg/L of SO₂ was added. After 24 h, musts were inoculated with 20 g hL⁻¹ of active dry yeast (Lavin EC-1118, Lallemand Inc., Canada). Density was recorded every 24 h, while temperature was measured every 6 h. Manual cap management followed a standardised extraction protocol based on must density: (i) from inoculation until cap formation, two punch-downs/day; (ii) from cap formation until 10 °Brix, three punch-downs/day; (iii) from 10 to 3 °Brix, two punch-downs/day; (iv) from 3 to 0 °Brix, two jar transfers plus addition of dry ice as CO₂ source; and (v) from 0 °Brix until alcoholic fermentation completion or a maximum of 13 days of maceration, addition of dry ice in the headspace. Fermentation was considered complete when wines contained < 2.5 g/L of reducing sugars. Total maceration time was standardised to 13 days. After maceration, 12 L of free-run wine was racked into 6 L glass containers. Malolactic fermentation was induced using 100 mg/L of *Oenococcus oeni* (Lavin VP41, Lallemand Inc.) and considered complete when malic acid levels were < 0.05 g/L (OenoFoss, FOSS Analytical A/S, Denmark).

Post malolactic fermentation, wines were racked, adjusted to 35 mg/L free SO₂, and aged for 3 months at 13–15 °C. No tartaric stabilisation was performed. Wines were bottled in 750 mL screw-cap bottles, and routine analyses (ethanol, total acidity, and pH) were carried out by FTIR spectroscopy (WineScan, FOSS Analytical, Denmark).

3. Analysis of Phenolic Compounds and Antioxidant Capacity

Replicates of wines from SS and for DS were analysed independently as individual samples, whose number varied according to the season as mentioned in the Site Characterisation section: 2016 (n = 3), 2017 (n = 4) and 2018 (n = 5). Then, measurements were performed

considering technical replicates of each individual sample per soil type and year: 3 for phenolic compounds, and 2 for antioxidant capacity, which were used for statistical analysis. Anthocyanins and low-molecular-weight polyphenols (LMWPs) were quantified by HPLC-DAD (Dionex Softron GmbH, Thermo Fisher Scientific, Germany) in wines two months after bottling, following Urvieta *et al.* (2018). For anthocyanins, 500 µL wine samples were evaporated and reconstituted prior to analysis using a Kinetex C₁₈ column for separation (Phenomenex, USA). Quantification was performed with malvidin-3-glucoside standard calibration (1–250 mg/L, r² = 0.998). For LMWPs, quantification was performed by external calibration using pure standards of compounds with linearity from 0.5 to 40 mg/L (r² > 0.998).

Antioxidant capacity was determined using the oxygen radical absorbance capacity (ORAC) assay in wines 5 months post-bottling, following Berli *et al.* (2015). Wine aliquots were diluted 1:750 v/v in 75 mM potassium phosphate buffer (pH 7.0). Aliquots (50 µL) of diluted samples and Trolox standards were added to a 96-well black plate. Then, 100 µL of fluorescein (20 nM solution) was added, and the mixture was incubated at 37 °C for 7 min before the addition of 50 µL of the peroxy radical generator AAPH [2,2'-azobis(2-amidinopropane) dihydrochloride (Sigma-Aldrich Inc., St. Louis, MO, USA), 140 mM solution]. Fluorescence was monitored using 485 nm excitation and 538 nm emissions at 1 min intervals during 90 min on a microplate fluorometer (Fluoroskan Ascent FL, Thermo Fisher Scientific Inc., Wilmington, DE, USA). The area under the curve of the fluorescence decay during 90 min was calculated, and the ORAC was expressed as mmol of Trolox equivalents (TE) per mL of wine.

4. Sensory Evaluation

The Triangle Test was used as a discriminative method to determine whether wines from different soils could be distinguished under blind conditions. Additionally, a Simple Paired Preference Test was conducted to assess which wine was preferred by the participants based on aroma and mouthfeel/taste (Lawless & Heymann, 2010). Tests were done in 4 months post-bottling wines by two panels: winemaking team (“Experts”) and winery staff with limited tasting experience (“Non-experts”). The panel included both women and men aged between 25 and 60 years, and its size increased annually to improve statistical robustness: 2016 (8 experts and 8 non-experts), 2017 (9 experts and 15 non-experts), and 2018 (15 experts and 26 non-experts). Results were expressed as the percentage of correct identifications.

In 2018, a trained panel conducted Descriptive Sensory Analysis (DA) by consensus in 7 months post-bottling wines, following Urvieta *et al.* (2018). Twelve panellists (aged 27–55) agreed to participate in the study through written informed consent and completed eight 1-hour training sessions: five for descriptor definition and three for DA. Twenty aroma descriptors and 7 mouthfeel/taste descriptors were defined using reference standards (Table S1). During the testing session, reference standards were available to refresh memory, and individual

sensory booths were used (Sensory Analysis Laboratory, INTA Mendoza, Argentina). Each sample consisted of 30 mL of wine at 20 °C in black tasting glasses (ISO 3591–1977), covered with plastic lids and coded with a three-digit random number. For each descriptor, the trained panellists rated the intensity of the wine on an unstructured linear scale, anchored with the terms “low” and “high” at each end. A 60-second break was included between each sample, during which the panellists cleaned their palates with water and salt-free crackers. The data were collected on the Soldesa software (Rodríguez *et al.*, 2014).

5. Statistical Analysis

Wine chemical composition was analysed by two-way ANOVA (soil type × season; $p < 0.05$), followed by Principal Component Analysis (PCA), biplot based on correlation matrix (mean-centred, unit-variance scaling), using Infostat software (Grupo Infostat, Di Rienzo *et al.* 2018). Triangle Test results were evaluated using binomial probability tables, paired preference results via the Friedman test ($p < 0.05$).

Descriptive sensory analysis (DA) data were analysed using the R software platform (version 3.2.2). Three-way ANOVA (panellist × wine × session) was applied (Lê *et al.*, 2015). For descriptors showing significant panellist × soil interaction, F-statistics were calculated using a pseudo-mixed model (Gay, 1998). Missing data were imputed with the “missMDA” package (Josse & Husson, 2016). PCA for sensory data was performed on the correlation matrix (no rotation), with 95 % confidence ellipses computed *via* the Hotelling test (Lê *et al.*, 2006) using the Panallipse function from the SensoMineR package (Husson *et al.*, 2005).

RESULTS

1. Harvest date and chemical characteristics of must and wine

Table 1 shows that grapes grown in SS reached maturity and were harvested 9–14 days earlier than those from DS across the 2016–2018 seasons, based on °Brix. In 2016, grapes

TABLE 1. Harvest date and chemical characteristics of wines for each soil type, both shallow and deep (SS and DS), and study season (2016, 2017, and 2018). Alcohol, titratable acidity (TA) and pH. Values are means ± SEM; different lowercase letters within a column indicate significant differences by soil type and season interaction (Fisher’s LSD; $p < 0.05$).

Season	Soil Type	Harvest date	Wine					
			Alcohol (% v/v)		TA (g/L)		pH	
2016	SS	06 Apr	13.15 ±0.15	d	6.66 ±0.10	a	3.34 ±0.02	c
	DS	15 Apr	11.97 ±0.15	e	6.35 ±0.10	bc	3.49 ±0.02	b
2017	SS	14 Mar	15.13 ±0.13	a	6.16 ±0.09	c	3.53 ±0.02	b
	DS	28 Mar	14.29 ±0.13	b	5.29 ±0.09	d	3.74 ±0.02	a
2018	SS	09 Mar	14.15 ±0.12	bc	6.54 ±0.08	ab	3.51 ±0.02	b
	DS	21 Mar	13.84 ±0.12	c	5.22 ±0.08	d	3.72 ±0.02	a
ANOVA								
$p(\text{soil:season})$			< 0.0001		0.0001		0.2068	

were harvested at 22 °Brix, associated with the colder and wetter conditions of that vintage, resulting in wines showing lower alcohol levels, higher titratable acidity (TA), and lower pH compared to subsequent years. In contrast, in 2017 and 2018 harvests occurred at 24 °Brix, producing wines with moderated alcohol content, higher pH, and lower TA relative to 2016. Within each vintage, SS wines consistently exhibited higher acidity than those from DS wines, and also showed higher alcohol content in 2016 and 2017.

2. Antioxidant capacity and phenolic composition in wines

Table 2 presents ORAC values, total anthocyanins, and anthocyanin groups based on the hydroxylation degree for SS and DS wines over the three seasons. In 2016, ORAC values were 9.4 % higher in SS wines, with no differences in 2017 and 2018. Total anthocyanin concentration was significantly higher in SS wines in 2016 (65 %) and 2017 (43 %), but not in 2018. Independent of the vintage, the anthocyanin content of SS wines was significantly higher compared to that of DS soil.

Most individual anthocyanins were more abundant in SS wines, except for malvidin, whose levels varied across years: 44 % higher in SS wines in 2016, similar between soil types in 2017, and 40 % higher in DS wines in 2018. As shown in the multifactorial ANOVA (Table S2), malvidin-3-O-glucoside represented 58 % of total anthocyanins and was not significantly affected by soil type. Cyanidin-3-O-glucoside, although representing only 1.2 % of total anthocyanins, was consistently elevated in SS wines, with an average increase of 71 % across the three seasons. Other abundant anthocyanins, such as petunidin-3-O-glucoside and delphinidin-3-O-glucoside, accounting for 11.8 % and 9.8 % of total anthocyanins, respectively, were increased on average by 47 % and 68 % in SS wines.

Figure 1 displays a PCA of anthocyanins grouped by acylation, hydroxylation, and methoxylation degrees. PC1 and PC2 explained 92 % of the total variance, with

TABLE 2. Multifactorial ANOVA for ORAC and Anthocyanins in wines from shallow soil (SS) and deep soil (DS) over three seasons (2016, 2017, and 2018). Values are means \pm SEM; different lowercase letters within a column indicate significant differences by soil type, season, or their interaction (Fisher's LSD; $p < 0.05$).

Soil Type	ORAC									
	Total Anthocyanin			Dihydroxylated			Trihydroxylated			
				Cyanidin	Peonidin	Delphinidin	Petunidin	Malvidin		
SS	360.6 \pm 4.4 a	613.8 \pm 24.4 a	11.7 \pm 0.5 a	45.9 \pm 2.2 a	89.0 \pm 3.6 a	103.4 \pm 4.0 a	363.7 \pm 15.8 a			
DS	345.2 \pm 4.4 b	477.4 \pm 24.4 b	3.3 \pm 0.5 b	23.5 \pm 2.2 b	34.4 \pm 3.6 b	60.9 \pm 4.0 b	344.3 \pm 15.8 a			
Season										
2016	389.7 \pm 6.1 a	459.7 \pm 33.7 b	6.2 \pm 0.7 b	33.1 \pm 3.1 a	46.6 \pm 5.0 b	65.3 \pm 5.6 b	308.6 \pm 21.8 b			
2017	380.6 \pm 5.3 a	646.6 \pm 29.2 a	9.5 \pm 0.6 a	37.4 \pm 2.7 a	83.8 \pm 4.3 a	103.6 \pm 4.8 a	412.4 \pm 19.9 a			
2018	288.3 \pm 4.8 b	513.9 \pm 26.1 b	6.8 \pm 0.6 b	33.6 \pm 2.4 a	54.9 \pm 3.9 b	77.7 \pm 4.3 b	340.9 \pm 16.9 b			
Soil: Season										
SS:2016	407.3 \pm 8.8 a	572.6 \pm 47.7 b	8.4 \pm 1.0 b	44.2 \pm 4.3 ab	67.3 \pm 7.0 bc	88.5 \pm 7.9 b	364.1 \pm 30.9 ab			
SS:2017	390.7 \pm 7.5 ab	761.8 \pm 41.3 a	15.9 \pm 0.9 a	55.4 \pm 3.8 a	118.5 \pm 6.1 a	128.8 \pm 6.8 a	443.1 \pm 26.8 a			
SS:2018	283.7 \pm 6.7 c	507.1 \pm 36.9 b	10.9 \pm 0.8 b	38.1 \pm 3.4 bc	81.3 \pm 5.4 b	92.9 \pm 6.1 b	283.9 \pm 23.9 bc			
DS:2016	372.1 \pm 8.7 b	346.8 \pm 47.7 c	3.9 \pm 1.0 c	22.0 \pm 4.3 d	25.8 \pm 7.0 d	42.1 \pm 7.9 d	253.1 \pm 30.9 c			
DS:2017	370.6 \pm 7.5 b	531.5 \pm 41.3 b	3.1 \pm 0.9 c	19.3 \pm 3.8 d	49.0 \pm 6.1 c	78.4 \pm 6.8 bc	381.7 \pm 26.8 a			
DS:2018	292.9 \pm 6.7 c	520.7 \pm 36.9 b	2.8 \pm 0.8 c	29.2 \pm 3.4 cd	28.4 \pm 5.4 d	62.4 \pm 6.1 cd	398.0 \pm 23.9 a			
ANOVA										
p(soil)	0.0250	0.0005	<0.0001	<0.0001	<0.0001	<0.0001	0.3956			
p(season)	<0.0001	0.0012	0.0041	0.4899	<0.0001	0.0002	0.0051			
p(soil:season)	0.0251	0.0086	0.0016	0.0047	0.1224	0.2899	0.0011			

W

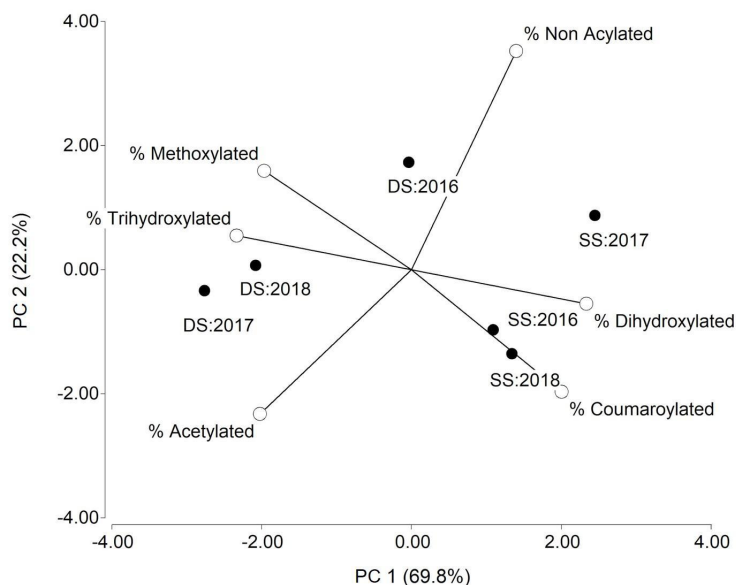


FIGURE 1. Principal component analysis of anthocyanins grouped by their degree of acylation, hydroxylation, and methoxylation in wines from superficial soil (SS) and deep soil (DS) over three seasons (2016, 2017, and 2018).

samples separating along PC1 according to soil profile. SS wines were associated with dihydroxylated, coumaroylated, and non-acylated anthocyanins, whereas DS wines were separated based on their higher content of trihydroxylated, methoxylated, and acetylated forms.

Table 3A–B shows the concentration of LMWPs in wines, grouped according to their biosynthetic families. Multifactorial ANOVA revealed strong seasonal effects, with the highest Total LMWPs levels in 2016, followed by 2017 and 2018. Several compounds showed consistent soil-related differences across all seasons. For instance, polydatin (a stilbene), astilbin (a dihydroflavonol), and quercetin (a flavonol) were consistently higher in SS wines over the three years (also visualised in Figure 2), reaching increases of 167 % (polydatin) and 99 % (astilbin). Other compounds, such as *trans*-resveratrol, caftaric acid, kaempferol-3-O-glucoside, and quercetin-3-O-glucoside, were also more abundant in SS wines, but not consistently across all seasons.

Conversely, *p*-coumaric acid and (-)-epicatechin concentrations were higher in DS wines across all seasons, while compounds such as caffeic acid, gallic acid, syringic acid, OH-tyrosol, (+)-catechin and (-)-gallocatechin were elevated in DS wines in a season-dependent manner. The seasonal and soil effects on *p*-coumaric acid are highlighted in Figure 2.

3. Sensory evaluations and descriptive sensory analysis by consensus

Table 4 summarises the results of the Triangle and Paired Preference Tests for the 2016, 2017, and 2018 vintages. On average, 90 % of expert panellists were able to distinguish between wines from shallow soils (SS) and deep soils (DS), compared to 56 % of non-expert participants.

Regarding preference, expert panellists consistently preferred wines from SS across all three seasons, as shown by lower mean rank values. These differences were statistically significant in 2016 and 2018, as indicated by different letters in the ANOVA column, but not in 2017.

In contrast, non-expert panellists tended to prefer wines from DS, although this trend was not statistically significant in any of the seasons, as all comparisons share the same significance group.

Consensus aroma and taste/mouthfeel attributes selected by the trained panel are listed in Table 5. Figure 3A presents the PCA biplot of 2018 sensory data, which accounted for 90.2 % of total variance (79.7 % for Dimension 1 and 10.6 % for Dimension 2). Wines were clearly separated by soil type, with tighter confidence ellipses for SS wines indicating less variability in sensory profiles. Figure 3B shows sensory descriptors contributing to soil type differentiation. Higher acidity and astringency, together with mint and alcohol aromas, were significantly associated with SS wines. In contrast, DS wines were characterised by sweeter flavours such as jam, along with green pepper, leather, and earthy notes. Several descriptors showed no significant differences between soil types, including mineral aroma.

TABLE 3A. Multifactorial ANOVA for LMWPs in wines from shallow soil (SS) and deep soil (DS) over the 2016, 2017, and 2018 seasons. Values are means \pm SEM; different lowercase letters within a column indicate significant differences by soil type, season, or their interaction (Fisher's LSD; $p < 0.05$).

Soil Type	Total LMWPs			Hydroxycinnamic acids				Hydroxybenzoic acids		Phenolic alc.
	t-Resveratrol	Polydatin	Caffeoyl	Caffeic	p-Coumaric	Gallic	Syringic	OH-Tyrosol		
SS	3.1 \pm 0.2 a	7.0 \pm 0.2 a	18.7 \pm 0.2 a	1.0 \pm 0.1 b	1.42 \pm 0.3 b	9.7 \pm 0.4 b	7.0 \pm 0.2 b	1.6 \pm 0.06 b		
DS	2.7 \pm 0.2 a	0.6 \pm 0.2 b	12.1 \pm 0.2 b	3.4 \pm 0.1 a	8.16 \pm 0.3 a	15.4 \pm 0.4 a	10.0 \pm 0.2 a	2.5 \pm 0.06 a		
Season										
2016	5.1 \pm 0.3 a	9.5 \pm 0.3 a	43.0 \pm 0.2 a	6.0 \pm 0.1 a	7.02 \pm 0.5 a	22.2 \pm 0.6 a	14.2 \pm 0.2 a	3.3 \pm 0.08 a		
2017	2.5 \pm 0.2 b	1.4 \pm 0.2 b	1.1 \pm 0.2 c	0.7 \pm 0.1 b	5.49 \pm 0.4 b	9.4 \pm 0.5 b	5.4 \pm 0.2 b	2.2 \pm 0.07 b		
2018	1.1 \pm 0.2 c	0.6 \pm 0.2 c	2.0 \pm 0.2 b	0.0 \pm 0.1 c	1.86 \pm 0.4 c	6.2 \pm 0.5 c	5.9 \pm 0.2 b	0.6 \pm 0.06 c		
Soil: Season										
SS:2016	7.9 \pm 0.4 a	17.1 \pm 0.4 a	52.2 \pm 0.3 a	3.1 \pm 0.2 b	4.26 \pm 0.7 b	13.7 \pm 0.8 b	10.2 \pm 0.3 b	2.1 \pm 0.12 b		
SS:2017	1.1 \pm 0.3 de	2.8 \pm 0.4 b	1.4 \pm 0.3 c	0.0 \pm 0.2 d	0.00 \pm 0.6 c	8.9 \pm 0.7 c	4.6 \pm 0.3 d	2.2 \pm 0.10 b		
SS:2018	0.3 \pm 0.3 e	1.2 \pm 0.3 c	2.4 \pm 0.2 c	0.0 \pm 0.1 d	0.00 \pm 0.5 c	6.5 \pm 0.6 d	6.3 \pm 0.2 c	0.5 \pm 0.09 c		
DS:2016	2.3 \pm 0.4 c	1.9 \pm 0.4 bc	33.8 \pm 0.3 b	8.8 \pm 0.2 a	9.8 \pm 0.7 a	30.6 \pm 0.8 a	18.3 \pm 0.3 a	4.5 \pm 0.12 a		
DS:2017	3.9 \pm 0.3 b	0.0 \pm 0.4 d	0.8 \pm 0.3 c	1.4 \pm 0.2 c	11.0 \pm 0.6 a	9.9 \pm 0.7 c	6.1 \pm 0.3 c	2.3 \pm 0.10 b		
DS:2018	1.9 \pm 0.3 cd	0.0 \pm 0.3 d	1.5 \pm 0.2 c	0.0 \pm 0.1 d	3.7 \pm 0.5 b	5.8 \pm 0.6 d	5.6 \pm 0.2 c	0.7 \pm 0.09 c		
ANOVA										
p (soil)	0.1641	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001		
p (season)	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001		
p (soil:season)	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001		

TABLE 3B. Multifactorial ANOVA for LMWPs in wines from shallow soil (SS) and deep soil (DS) over the 2016, 2017, and 2018 seasons. Values are means \pm SEM; different lowercase letters within a column indicate significant differences by soil type, season, or their interaction (Fisher's LSD; $p < 0.05$).

Soil Type	Dihydroflavonol			Flavonols			Flavanols		
	Asiflbin	Kaempferol-3-glu	Quercetin-3-glu	Quercetin	(+)-Catechin	(-)-Epicatechin	(-)-Gallocatechin		
SS	6.18 \pm 0.28 a	0.90 \pm 0.05 a	0.39 \pm 0.02 a	10.76 \pm 0.33 a	19.12 \pm 1.06 b	10.67 \pm 0.39 b	10.56 \pm 0.22 a		
DS	3.10 \pm 0.28 b	0.62 \pm 0.05 b	0.05 \pm 0.02 b	2.29 \pm 0.33 b	25.88 \pm 1.06 a	19.60 \pm 0.39 a	9.99 \pm 0.22 a		
Season									
2016	6.48 \pm 0.38 a	0.71 \pm 0.06 a	0.10 \pm 0.03 b	5.8 \pm 0.46 b	41.35 \pm 1.47 a	27.15 \pm 0.54 a	21.86 \pm 0.31 a		
2017	4.95 \pm 0.33 b	0.78 \pm 0.06 a	0.57 \pm 0.03 a	11.23 \pm 0.40 a	24.33 \pm 1.27 b	14.03 \pm 0.46 b	6.78 \pm 0.27 b		
2018	2.49 \pm 0.30 c	0.78 \pm 0.05 a	0.00 \pm 0.03 c	2.55 \pm 0.36 c	1.82 \pm 1.14 c	4.22 \pm 0.42 c	2.18 \pm 0.24 c		
Soil: Season									
SS:2016	7.88 \pm 0.54 a	0.94 \pm 0.09 a	0.19 \pm 0.04 b	11.61 \pm 0.65 b	30.08 2.07 b	18.17 \pm 0.76 b	20.39 \pm 0.44 b		
SS:2017	6.78 \pm 0.47 a	1.09 \pm 0.08 a	0.99 \pm 0.03 a	17.23 \pm 0.56 a	25.84 \pm 1.80 bc	12.07 \pm 0.66 d	8.55 \pm 0.38 c		
SS:2018	3.87 \pm 0.42 bc	0.66 \pm 0.07 b	0.00 \pm 0.03 c	3.46 \pm 0.50 d	1.43 \pm 1.61 d	1.77 \pm 0.59 f	2.75 \pm 0.34 e		
DS:2016	5.08 \pm 0.54 b	0.48 \pm 0.09 b	0.00 \pm 0.04 c	0.00 \pm 0.65 e	52.61 2.07 a	36.14 \pm 0.76 a	23.34 \pm 0.44 a		
DS:2017	3.12 \pm 0.47 c	0.48 \pm 0.08 b	0.14 \pm 0.03 b	5.23 \pm 0.56 c	22.82 \pm 1.80 c	15.99 \pm 0.66 c	5.01 \pm 0.38 d		
DS:2018	1.11 \pm 0.42 d	0.89 \pm 0.07 a	0.00 \pm 0.03 c	1.64 \pm 0.50 e	2.21 \pm 1.61 d	6.67 \pm 0.59 e	1.62 \pm 0.34 f		
ANOVA									
p (soil)	<0.0001	0.0005	<0.0001	<0.0001	0.0003	<0.0001	0.0872		
p (season)	<0.0001	0.6732	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001		
p (soil:season)	0.5681	0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001		

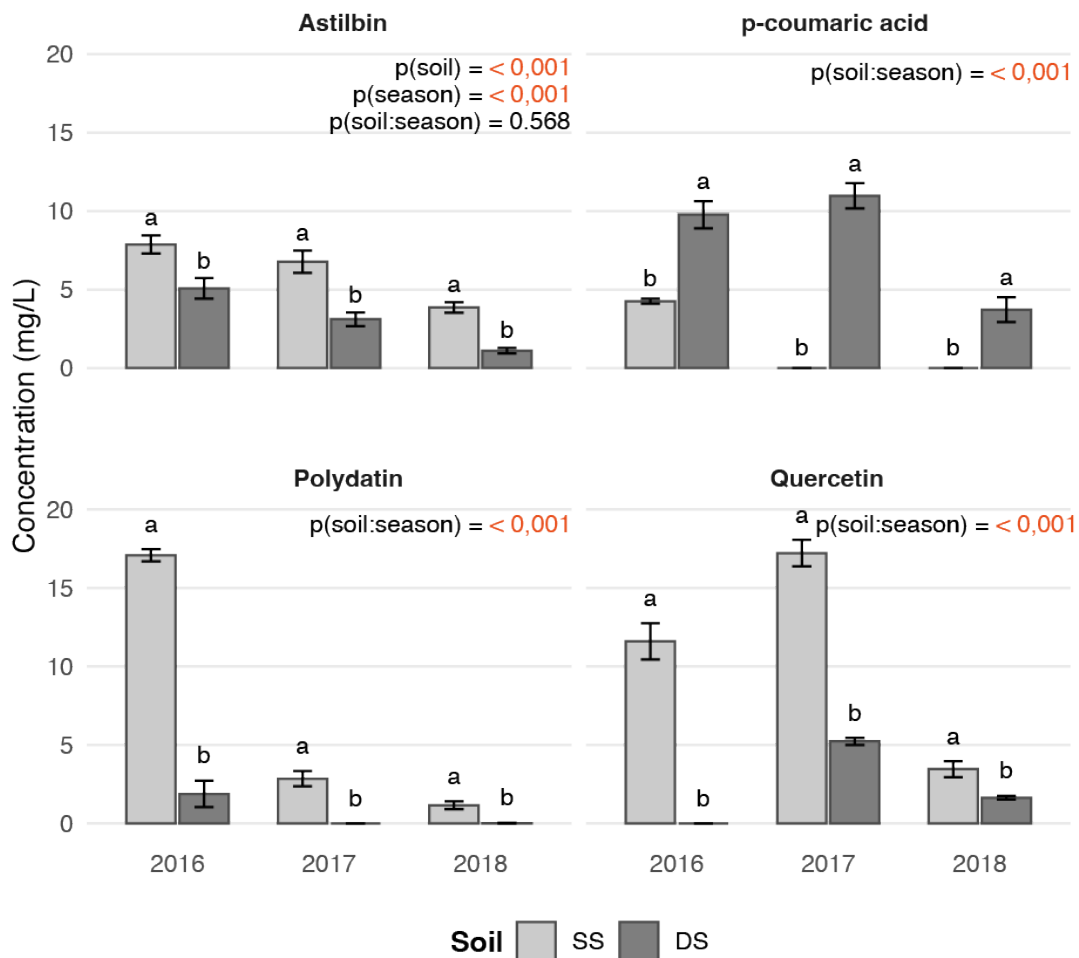


FIGURE 2. Multifactorial ANOVA for astilbin (A), *p*-coumaric acid (B), quercetin (C) and polydatin (D) in wines from shallow (SS) and deep soil (DS) over 2016–2018. Values are means \pm SEM; different lowercase letters indicate significant differences (Fisher’s LSD; $p < 0.05$).

TABLE 4. Triangle and Paired Preference Tests on wines from deep (SS) and shallow (DS) soils, 2016–2018, evaluated by Expert and Non-expert panels. Different letters indicate significant differences (Friedman; $p < 0.05$).

Category	Triangle Test				Preference Test		
	Season	Number of panellists	Correct answers (%)	<i>p</i> -value	Soil Type	Rank (mean)	Significance
Expert	2016	8	87.5	0.0026	SS	1.13	b
					DS	1.88	a
	2017	9	100.0	<0.0001	SS	1.33	a
					DS	1.67	a
	2018	15	86.7	<0.0001	SS	1.07	b
					DS	1.93	a
Non-Expert	2016	8	50.0	0.2586	SS	1.63	a
					DS	1.38	a
	2017	15	53.3	0.0882	SS	1.60	a
					DS	1.40	a
	2018	26	65.4	0.0008	SS	1.58	a
					DS	1.42	a

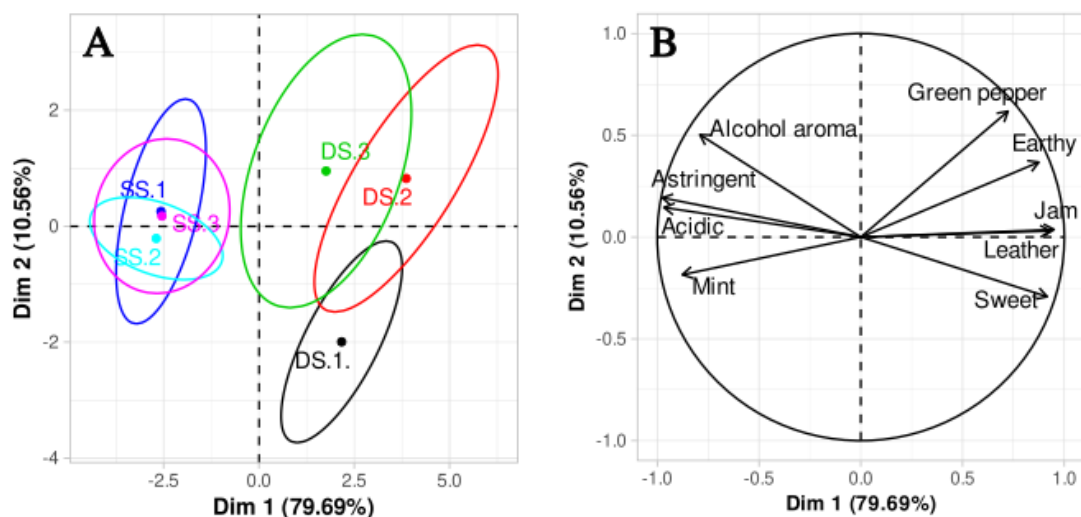


FIGURE 3. Principal component analysis (PCA) biplot based on correlation matrix (mean-centred, unit-variance scaling) of the data from the descriptive sensory analysis by consensus of deep and shallow soil wines (DS and SS) conducted by the trained panel in 2018. (A) confidence ellipses based on the multivariate distribution of Hotelling's test for $p < 0.05$, indicating 95 % confidence intervals and (B) sensory loadings.

TABLE 5. Aromatic and taste/mouthfeel attributes of 2018 Malbec wines for shallow (SS) and deep (DS) soils. Values are means \pm SEM from trained panel ($n = 12$); different letters indicate significant differences by soil type (Fisher's LSD; $p < 0.05$).

Attribute	SS	DS	p(soil)	p(soil:panellist)
Jam	6.6 \pm 0.3 b	7.6 \pm 0.3 a	0.0058	0.0001
Green pepper	4.2 \pm 0.2 b	5.3 \pm 0.2 a	0.0020	<0.0001
Leather	4.2 \pm 0.3 b	5.2 \pm 0.3 a	0.0092	0.8253
Earthy	3.8 \pm 0.2 b	4.3 \pm 0.2 a	0.0252	0.0004
Sweet	6.4 \pm 0.2 b	7.8 \pm 0.2 a	<0.0001	0.0266
Acidic	8.7 \pm 0.2 a	6.8 \pm 0.2 b	<0.0001	0.0013
Astringent	10.1 \pm 0.2 a	6.3 \pm 0.2 b	<0.0001	<0.0001
Mint	6.3 \pm 0.2 a	5.2 \pm 0.2 b	0.0002	<0.0001
Alcohol (aroma)	7.7 \pm 0.3 a	6.9 \pm 0.3 b	0.0205	0.4550
Pepper	6.7 \pm 0.2 a	6.3 \pm 0.2 a	0.1993	<0.0001
Dried fruits	4.5 \pm 0.2 a	4.4 \pm 0.2 a	0.7782	0.7646
Chocolate	4.4 \pm 0.2 a	4.4 \pm 0.2 a	0.9102	0.0438
Mineral	6.4 \pm 0.3 a	6.0 \pm 0.3 a	0.2863	0.1074
Oak	5.1 \pm 0.2 a	4.9 \pm 0.2 a	0.4340	0.0010
Fig	5.6 \pm 0.3 a	6.0 \pm 0.3 a	0.2650	0.0378
Bitter	4.6 \pm 0.2 a	4.9 \pm 0.2 a	0.2253	0.3875
Plum	7.1 \pm 0.3 a	7.3 \pm 0.3 a	0.6693	0.4570
Roses	5.4 \pm 0.2 a	5.2 \pm 0.2 a	0.5303	0.0474
Spicy	6.9 \pm 0.2 a	7.1 \pm 0.2 a	0.4051	0.0067
Alcohol (mouth)	8.3 \pm 0.2 a	8.2 \pm 0.2 a	0.7218	0.0030
Violet	7.8 \pm 0.3 a	7.7 \pm 0.3 a	0.7297	0.7483
Tea	5.4 \pm 0.3 a	5.0 \pm 0.3 a	0.2719	0.3462

DISCUSSION

The 2016 vintage was exceptionally distinct, with unusually high rainfall and humidity for the Mendoza region. In fact, average summer rainfall in 2016 reached 604 mm, compared to a 10-year average of 245 mm (unpublished data from the Catena Institute of Wine weather stations). The growing degree days (GDD) were 1225 in 2016, 1438 in 2017, and 1432 in 2018 (Urvieta *et al.* 2021). Grape harvest criteria were based on total soluble solids (TSS) to achieve uniform maturity and minimise differences in composition due to ripeness. Across the three seasons (2016–2018), grapes from SS reached harvestable maturity 9 to 14 days earlier than those from DS. A similar effect of soil effective depth on ripening was observed by Roig-Puscama *et al.* (2025), who reported advances of 3, 7, and 12 days for Malbec grapes from SS compared to DS across three vintages in Paraje Altamira (San Carlos, Mendoza).

In 2016, delayed sugar accumulation under cold and wet conditions postponed harvest to April at 22 °Brix, later than in other seasons, where grapes were harvested in March. The decision aimed to prevent further delays that could compromise grape health.

The higher acidity in SS wines may reflect earlier harvest dates (9–14 days) despite targeting similar °Brix, as organic acid degradation is less advanced in earlier-picked grapes (Urvieta *et al.*, 2021). Although harvest °Brix was targeted uniformly, SS wines consistently showed slightly higher alcohol, likely due to reduced water availability in this soil type, concentrating sugars in the berries (Berli *et al.*, 2015; Mezzatesta *et al.*, 2022).

Environmental stressors such as solar UV-B exposure and water restriction are known to significantly affect the profiles of anthocyanins and other LMWPs in berry skins, often enhancing the concentration of compounds with higher antioxidant capacity (Berli *et al.*, 2011; Berli *et al.*, 2015; Alonso *et al.*, 2016). Previous studies on alluvial soils have shown that vines on DS maintain better water status than those on SS, affecting photoassimilate allocation, and vegetative growth (Mezzatesta *et al.*, 2022; Roig-Puscama *et al.*, 2025), which influences the microclimatic conditions at cluster level (humidity, temperature, solar UV-B intensity), on the vines growing on different soil types and hence, fruit yield and total phenolic accumulation in berry skins (Mezzatesta *et al.*, 2022).

Anthocyanin composition is genetically driven, and it can be modified by environmental factors that regulate gene expression and biosynthetic pathways during berry ripening (Castellarin *et al.*, 2007). Moreover, by chemical transformations induced by fermentation and copigmentation processes. Our wine analysis showed that SS wines contained a higher proportion of dihydroxylated anthocyanins, particularly cyanidin derivatives, and a greater proportion of non-acylated and *p*-coumaroylated anthocyanins than DS wines.

Cyanidin and delphinidin, produced via the action of glycosylation enzyme UFGT, are primary anthocyanins for which the hydroxylation of the B-ring influences their antioxidant potential. Further downstream, O-methyltransferases convert cyanidin into, and delphinidin into petunidin and malvidin (Castellarin *et al.*, 2006). These modifications, glycosylation, hydroxylation, and methoxylation, affect both pigment stability and antioxidant capacity (Sroka, 2005). Among these, cyanidin exhibits the highest antioxidant potential, while malvidin shows the lowest but provides greater oxidative stability (Wang *et al.*, 1997; Cheng *et al.*, 2014; Sroka, 2005). Increased cyanidin levels in response to stressors like UV-B were previously reported in Malbec (Berli *et al.*, 2011), while Bindon *et al.* (2008) showed that partial root drying increased total anthocyanins but reduced the proportion of methoxylated forms, enhancing antioxidant properties. This previous result could be connected with the lower water availability (stress) of SS wines reported in the present work. Non-acylated anthocyanins, more abundant in SS wines, are also associated with higher antioxidant potential (Sroka, 2005). Environmental stress can also stimulate anthocyanin biosynthesis through enhanced photoassimilate allocation to the berries (Yu *et al.*, 2020), and smaller berry sizes, as found in SS vines, can lead to concentration effects (Ojeda *et al.*, 2002; Mezzatesta *et al.*, 2022).

Regarding LMWPs, soil type did not consistently affect total content. For example, DS wines in 2016 had higher levels due to increased flavanols and hydroxybenzoic acids. However, specific compounds were consistently more abundant in SS wines across all seasons, particularly polydatin, astilbin and quercetin. Polydatin is a precursor of trans-resveratrol, a compound with strong antioxidant activity responding to UV-B (Su *et al.*, 2013; Luan *et al.*, 2014; Alonso *et al.*, 2016). Astilbin, a dihydroflavonol and flavonol precursor (Bogs *et al.*, 2005), is known for its antioxidant and antimicrobial properties (Liu *et al.*, 2020). Its accumulation has been linked to abiotic stress responses, including UV-B and oxidative stress, suggesting a potential protective role in grape berry physiology. Quercetin, considered one of the most potent antioxidant phenolics (Iacopini *et al.*, 2008), increased in berry skins and leaves exposed to increased UV-B (Berli & Bottini, 2013). Similarly, elevated trans-resveratrol and quercetin levels in wines from high-elevation vineyards in Tunuyán and Tupungato were observed by Urvieta *et al.* (2018), supporting the differential phenolic enrichment in stress-related environments, which relates well with the results of this work in the more stressful conditions of SS, a frequent soil profile present in the heterogeneous Uco Valley region where Malbec vineyards are located.

Hydroxycinnamic and hydroxybenzoic acids play a key role in stabilising wine colour through copigmentation, and their levels are linked to ripeness and stress (Ribéreau-Gayon *et al.*, 2006; Malaj *et al.*, 2013). Typically, these phenolic acids are more abundant under lower stress conditions (Berli *et al.*, 2011), possibly explaining their higher concentration in DS wines. The early harvest at

22 °Brix in 2016 likely contributed to the elevated flavanol content, which generally declines later in ripening due to polymerisation (Downey *et al.*, 2003; Berli *et al.*, 2011; Yu *et al.*, 2020).

The chemical differences between wines from SS and DS soil were also reflected in their aromatic and sensory profiles. Soil influences aroma compounds in grapes, where those with shallow and stony profiles often enhance fruity notes, while deeper, clay-rich soils tend to promote spicy aromas (Koundouras, 2018). However, aroma development is highly complex, affected by soil, climate, plant vigour, phenology and winemaking practices (Ilc *et al.*, 2016; Scarlett *et al.*, 2014; Ferretti and Febbroni, 2022; Van Leeuwen *et al.*, 2004). In the present study, we found that many of the sensory profiles of Malbec wines were affected by the studied soils. In accordance with the results of chemical profiles, SS wines were consistently separated in sensory analysis, independently of the vintage, from those of DS. This point highlights the prevalence of terroir-driven factors over vintage. However, sensory descriptors associated with the different soil types differed from those reported by other authors. Roig-Puscama *et al.* (2025) found that wines from DS showed greater vintage variability, suggesting a stronger influence of interannual conditions, whereas those from SS were more consistent, possibly reflecting a dominant soil-type (terroir-driven) effect over climatic variation. Moreover, reported that wines from SS showed more intense plum aromas and were characterised by greater colour intensity, structure, astringency, and lower acidity.

The perception of aroma minerality in the present study differed from others, who reported that it is typically associated with calcareous soils like SS (Ballester *et al.*, 2013; Roig-Puscama *et al.*, 2025). Other volatile compounds may modulate minerality perception, suggesting the need for a more standardised sensory definition (Tominaga *et al.*, 2000). In the present study, we did not assess mineral perception in the mouth. Likewise, the effect on wine colour was not specifically evaluated. The trained panel selected 20 aromatic descriptors across samples, compared to 11 reported by Roig-Puscama *et al.* (2025). Therefore, the observed differences may be attributed not only to soil type but also to site and vine selection, as well as to differences in descriptor definition and panel criteria.

SS wines from 2018 were associated with greater astringency, a sensory attribute previously linked to tannin concentration and polymer size (Koundouras, 2018). Although these chemical parameters were not evaluated in the present study, the water stress experienced in SS wines likely promoted increased tannin accumulation and polymerisation, potentially contributing to the enhanced perception of astringency.

Expert panel preferences favoured SS wines in 2016 (colder and rainy vintage) and 2018 (warmer and drier vintage), but showed no preference in 2017, when both treatments experienced similar environmental stress. This suggests that soil-driven differences could be more perceptible under extreme climatic conditions. The lack of consistent preference

among non-expert tasters may reflect low statistical power in early vintages (2016: n = 8 vs. 2018: n = 26). In contrast, non-expert tasters tended to evaluate the wines based on a more global and hedonic impression, showing lower consistency when the differences between samples depended on structural or origin-related attributes. This pattern persists even under blind tasting conditions. This interpretation is consistent with previous works showing that expertise shapes both perceptual calibration and the use of sensory information. In fact, expert tasters apply a more stable sensory framework and are better able to connect sensory differences to environmental factors such as soil- or climate-driven variations, whereas non-experts do not consistently link these cues with vineyard conditions (Ballester *et al.*, 2013; Ferretti & Febbroni, 2022).

A hypothesis, consistent with expert sensory behaviour reported in the literature, although not directly testable with the present data, is that expert preferences may also reflect their experience assessing wines with higher phenolic concentration or greater ageing potential. Even under blind conditions, experts may partially project the expected future development of the wine when evaluating balance and structure. Non-expert tasters, by contrast, may prioritise immediate drinkability, favouring wines that are less concentrated and more approachable in their youth. Differences in these perceptual and evaluative frameworks could, therefore, contribute to the divergence in preferences observed between the two groups.

CONCLUSIONS

This study demonstrates that shallow soils (SS) consistently yield Malbec with: (1) higher dihydroxylated anthocyanins (*e.g.*, cyanidin-3-glucoside; +71 % avg.) and non-acylated forms; (2) elevated stress-responsive LMWPs (polydatin: +167 %, astilbin: +99 %, and quercetin); and (3) enhanced astringency and acidity, possibly corresponding with the higher environmental stress experienced by vines growing under limited soil effective depth conditions.

Several descriptors were used to characterise and differentiate wines from shallow and deep soils, giving insights for the typification of Malbec in the context of intra-vineyard soil effective depth. Expert tasters recognised wines as different, while a higher number of people is needed to analyse this trend among non-expert panellists.

Within the bounds of this observational, multi-vintage design, this research highlights those variations in soil profile influence wine style and quality in a consistent manner. That is, wines from both contrasting intra-vineyard soil effective depths were consistently separated across vintages. Beyond local implications, this work highlights those variations in soil profile characteristics should be considered in site selection and vineyard management strategies aimed at producing terroir-driven wines.

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