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Article

ROOTSTOCK AND HARVEST SEASON IMPACT ON THE CHEMICAL COMPOSITION OF WINES FROM PORTUGUESE AND SPANISH CLONES OF ‘ARAGONEZ’ (SYN. ‘TEMPRANILLO’) CULTIVAR (*VITIS VINIFERA* L.) IN A TROPICAL SEMI-ARID CLIMATE OF NORTHEASTERN BRAZIL

IMPACTO DO PORTA-ENXERTO E DA ÉPOCA DE COLHEITA NA COMPOSIÇÃO QUÍMICA DE VINHOS PRODUZIDOS COM CLONES PORTUGUESES E ESPANHÓIS DA CULTIVAR ‘ARAGONEZ’ (SIN. ‘TEMPRANILLO’) (*VITIS VINIFERA* L.) EM CLIMA TROPICAL SEMIÁRIDO DO NORDESTE DO BRASIL

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SUMMARY

Portuguese and Spanish clones from ‘Aragonez’ grapevine (*syn*. ‘Tempranillo’), although considered synonyms, exhibit distinct responses when combined with different rootstocks and harvest seasons under the tropical semi-arid climate of the São Francisco Valley, northeastern Brazil. This study evaluated the effects of four rootstocks (‘IAC313’, ‘IAC572’, ‘P1103/Paulsen’, and ‘SO4’) over four consecutive vintages, considering two harvests per year, on the yield and physicochemical composition of red wines. Wine composition was primarily influenced by harvest season, followed by clone origin and rootstock. Second-semester harvests promoted higher alcohol content, pigment levels, phenolic compounds, tanning power, and antioxidant capacity, whereas the 2016_1 harvest, under heavy rainfall, showed lower potential. Among rootstocks, ‘SO4’ was associated with higher flavonoid content, polymeric pigments, copigmentation, and antioxidant capacity, particularly in Spanish clones, although it showed lower yield in some semesters. In contrast, ‘IAC313’ maintained higher productivity, highlighting the importance of rootstock–clone interactions for vine performance in tropical regions. The predominance of polymeric tannins and high tanning power indicated wines with greater ageing potential and sensory complexity. Strong correlations between tannins, anthocyanins, and antioxidant capacity underlined the important role of phenolics in wine quality and bioactivity. Multivariate analysis showed that classical composition variables discriminated samples better than monomeric anthocyanin profiles. These results emphasize the need for adaptative viticultural and oenological strategies, such as harvest scheduling, informed rootstock selection, and tailored winemaking practices, to improve quality, productivity, and stability of tropical wines.

RESUMO

Clones portugueses e espanhóis da casta ‘Aragonez’ (*syn*. ‘Tempranillo’), embora considerados sinônimos, apresentam respostas distintas quando combinados com diferentes porta-enxertos e épocas de colheita no clima tropical semiárido do Vale do São Francisco, nordeste do Brasil. Este estudo avaliou os efeitos de quatro porta-enxertos (‘IAC313’, ‘IAC572’, ‘P1103/Paulsen’ e ‘SO4’) ao longo de quatro safras consecutivas, considerando duas colheitas por ano, sobre a produtividade e composição físico-química de vinhos tintos. A composição dos vinhos foi principalmente influenciada pela época de colheita, seguida pela origem do clone e do porta-enxerto. As colheitas do segundo semestre promoveram maior teor alcoólico, pigmentos, compostos fenólicos, poder tanante e capacidade antioxidante, enquanto a colheita 2016_1, sob chuvas intensas, apresentou menor potencial. Entre os porta-enxertos, ‘SO4’ esteve associado a maior teor de flavonoides, pigmentos poliméricos, copigmentação e capacidade antioxidante, especialmente em clones espanhóis, embora tenha apresentado menor produtividade em alguns semestres. Em contraste, ‘IAC313’ manteve maior produtividade, evidenciando a importância da interação porta-enxerto-clone no desempenho da videira em regiões tropicais. A predominância de taninos poliméricos e elevado poder tanante indicou vinhos com maior potencial de envelhecimento e complexidade sensorial. Fortes correlações entre taninos, antocianinas e capacidade antioxidante destacaram o importante papel dos fenólicos na qualidade e bioatividade dos vinhos. A análise multivariada mostrou que as variáveis clássicas de composição discriminaram melhor as amostras do que os perfis de antocianinas monoméricas. Os resultados reforçam a necessidade de estratégias vitícolas e enológicas adaptativas, como programação da colheita, escolha adequada de porta-enxertos e práticas de vinificação, visando melhorar a qualidade, a produtividade e a estabilidade de vinhos tropicais.

Keywords: Tropical red wines, São Francisco Valley, harvest season, rootstock affinity, chemical composition.
Palavras-chave: Vinhos tintos tropicais, Vale do São Francisco, época de colheita, afinidade porta-enxerto, composição química.

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INTRODUCTION

The Submiddle São Francisco Valley, located in northeastern Brazil, has a tropical semi-arid climate where vineyards can produce more than two harvests per year in a continuous cycle. Pruning and harvesting times are defined by the producer according to rainfall, market demand, infrastructure, and intended wine style (Pereira, 2020; Pereira *et al*., 2020).

Grapevines pruned between May and August experience more favorable thermos-hydrological conditions for tropical wine production, with the second semester characterized by higher temperatures that accelerate grape ripening (Teixeira *et al*., 2018; Oliveira *et al*., 2018). The use of different varieties and rootstock interactions across harvest seasons may improve wine quality, since each cultivar–clone/rootstock combination responds differently to environmental and physiological factors (Santos *et al*., 2019).

The main grapevine varieties (*Vitis vinifera* L.) used for red wine production in this region are ‘Syrah’, ‘Tempranillo’, ‘Aragonez’, ‘Cabernet Sauvignon’, ‘Alicante Bouschet’, and ‘Touriga Nacional’ (Padilha *et al*., 2016; Oliveira *et al*., 2019a,b; Oliveira *et al*., 2020), and ‘‘Syrah’’ is the most widely planted and studied cultivar.

‘Tempranillo’ is the fifth most cultivated worldwide (OIV, 2017), with significant plantings in Spain (203247 ha) and Portugal (18119 ha). The Vitis International Variety Catalogue (VIVC, www.vive.de) (Ibáñez *et al*., 2012) lists nearly 66 synonyms for this cultivar, including ‘Aragonez’ and ‘Tinta Roriz’ (Alifragkis *et al*, 2015). Its economic importance and wide distribution across different terroirs have motivated clonal selection programs to improve adaptation and quality (Ibáñez *et al*., 2015; Lemos *et al*., 2020). In the São Francisco Valley, ‘Syrah’ and ‘Tempranillo’ vines are well established among wineries due to their notable adaptation to the semi-arid tropical climate (Dantas *et al*., 2023). However, few studies have addressed their performance in relation to grape, rootstock, and harvest season interactions.

The main challenges for tropical viticulture are to expand knowledge on vine adaptation to tropical climates and to their constraints, and explore innovative cultivation systems. The interaction between genotype and rootstock, under specific soil and climatic conditions, enables the selection of suitable combinations for vineyard management, favoring productivity and wine quality when combined with appropriate winemaking practices (Carbonneau, 2011; Albacete *et al*., 2015; Suriano *et al*., 2016, Pereira, 2020).

The objective of this study was to evaluate the impact of rootstock, harvest season, and their interactions on the physicochemical composition of tropical red wines produced from grapevine clones of the cultivar ‘Aragonez’ (*Vitis vinifera* L.), originally from Portugal and Spain, respectively known as ‘Aragonez’ and its synonym ‘Tempranillo’, grown under the semi-arid tropical climate of northeastern Brazil.

MATERIALS AND METHODS

Chemicals and standards

Analytical-grade methanol, diethyl ether, ethyl acetate, acetic acid, and acetone were purchased from Fisher Scientific (Loughborough, United Kingdom). A pure standard of malvidin-3-*O*-glucoside was obtained from Extrasynthese (Genay, France). Ethanol, formic acid, acetonitrile, acetaldehyde, and formaldehyde were purchased from Honeywell (Seelze, Germany). Vanillin, sodium metabisulphite, sodium hydroxide, tartaric acid, potassium hydroxide, methanol, bovine albumin, and sulphuric acid were supplied by Sigma-Aldrich (St. Louis, USA).

Experimental design

The study was conducted in an experimental vineyard located in a tropical semi-arid climate, at a partner winery in Pernambuco State, Brazil, on the banks of the São Francisco River (9°2′ S, 40º11′ W), at approximately 350 m above sea level. The vineyard was established in 2006 and trained using a single-wire trellis system. The experimental plot followed a randomized complete block design, with fifty vines selected per cultivar × rootstock combination, distributed across different rows and positions (ten vines per block, located at the beginning, middle, and end of the vineyard) to minimize soil variability. Vines were oriented in a north-south direction and spaced at 1 m between plants and 3 m between rows (3,333 vines/ha), using drip irrigation with emitters delivering 4.0 L/h, spaced 1 m apart. All vines were uniformly spur-pruned and trained on a bilateral cordon.

A total of ten (n = 10) grapevine clones of the ‘Aragonez’ cultivar (*syn*. ‘Tempranillo’), originating from Portugal and Spain, were selected for this study, comprising five Portuguese and five Spanish clones. All clones were grafted onto four different rootstocks: ‘P1103/Paulsen’ (*V. berlandieri* × *V. rupestris*), ‘SO4’ (*V. berlandieri* × *V. riparia*), ‘IAC313’ (*V. riparia* × *V. rupestris* × *V. cinerea*) and ‘IAC572’ (*V. riparia* × *V. rupestris* × *V. caribaea*). Four consecutive harvests were evaluated: March 2015 (first semester, 2015_1); September 2015 (second semester, 2015_2); February 2016 (first semester, 2016_1); August 2016 (second semester, 2016_2). Grapes were harvested on the same date per season, as determined by the winery, with each harvest date based on the oenological maturity of the grapes, particularly the °Brix-to-total acidity ratio, while considering climate conditions and grape health (Figure 1).

The regional climate is classified as BSwh under the Köeppen Climate Classification System, corresponding to a very hot semi-arid zone. The soils are classified as yellow eutrophic Argisol (soil taxonomy: Alfisol) (Oliveira *et al*., 2019b).

Vinification of monovarietal wines

Considering the logistical challenges of processing the total grape volume, each clone × rootstock interaction was treated as a single sample, and the evaluation was conducted separately for the groups of five Portuguese-origin clones (cv. ‘Aragonez’) and five Spanish-origin clones (*syn*. cv. ‘Tempranillo’). Accordingly, two wines were produced for each rootstock assessed, using a total of 40 kg of grapes per cultivar × rootstock interaction, corresponding to 8 kg per clone, with berry weight equally distributed among the clones within each group. Grapes were manually destemmed, crushed, sulfited (50 mg/L SO_2), and the resulting homogeneous musts were brought to 25 °C and inoculated with a selected active dry yeast (*Saccharomyces cerevisiae* var. *Bayanus* - 200 mg/L), to undergo traditional red wine vinification. Maceration time and contact with solid parts were standardized across all treatments for 7 days at 25 °C, with reassembly performed once per day by rack-and-return modality. After alcoholic fermentation, confirmed by stable density and alcohol content, the wines underwent spontaneous malolactic fermentation at 18 °C, monitored until completion using chromatography paper (OIV, 2014). At the end of malolactic fermentation, wines were corrected with sulfur dioxide (30 mg/L^{-}SO_2) and stabilized by cold incubation at 0 °C for 30 days, during which natural settling of the lees occurred. The wines were manually bottled in 0.75 L glass bottles, sealed with agglomerated cork stoppers, and stored for 30 days at 18 ± 2 °C in the cellar for stabilization. Samples were then transported by air to Lisbon, Portugal, in boxes with thermal control, arriving the following day, and stored at 18 ± 2 °C until analysis at the University of Lisbon (ISA).

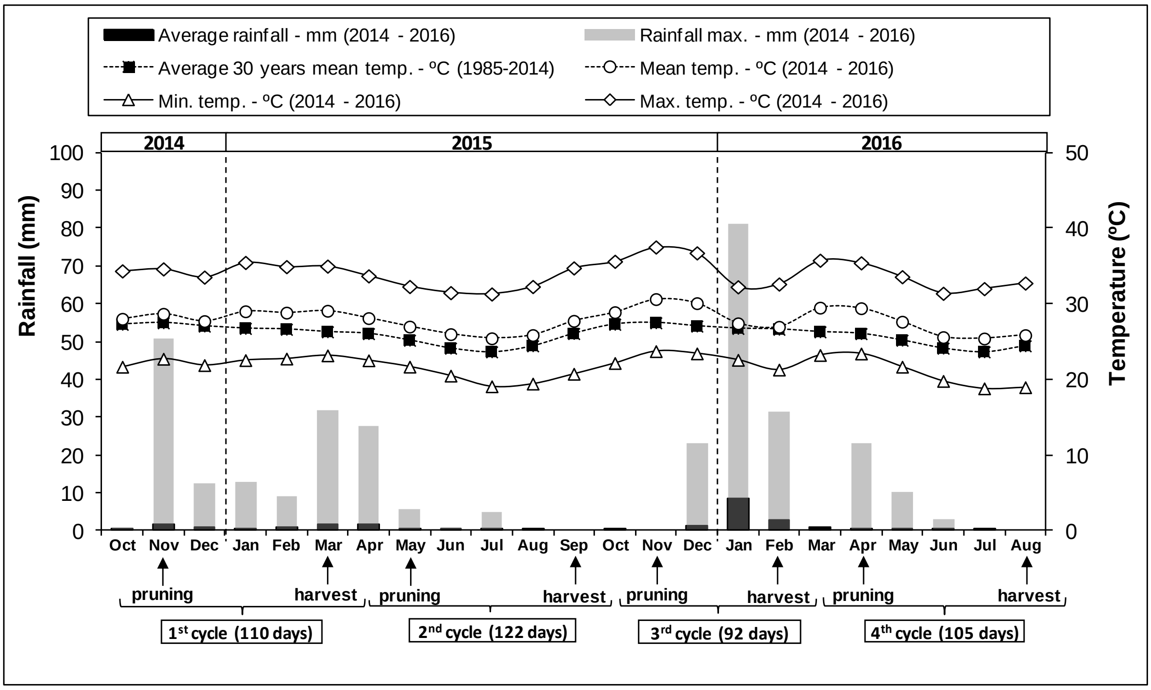

Figure 1. Meteorological data including average and maximum rainfall, as well as maximum, mean, and minimum temperatures, recorded during the harvest seasons and years of study in the state of Pernambuco, tropical semi-arid region of Brazil.

Wine chemical analysis: classical's, color and global phenolic parameters

All wines were analyzed six months after bottling. The classical parameters (alcohol content, pH, total and volatile acidity, dry extract, residual sugar and free and total sulfur dioxide) were analyzed according to the standardized methods proposed by the International Organization of Vine and Wine (OIV, 2014). The colorimetric parameters analysed were: total anthocyanins (Ribéreau-Gayon and Stonestreet, 1965); colored anthocyanin (Somers and Evans, 1977); total phenols (Ribéreau-Gayon, 1970); flavonoids and non-flavonoids (Kramling and Singleton, 1969); anthocyanin copigmentation (Boulton, 2001); color intensity and hue (OIV, 2014); total and polymeric pigments (Somers and Evans, 1977); and tanning power (De Freitas and Mateus, 2001). The calculation of the ionization index (%), polymeric pigments index (%) and copigmentation (%) followed the methodology of Somers and Evans (1977), which is based on the decolorization of anthocyanins after excessive addition of SO_2, the expression of anthocyanins in the flavylium form at $pH < 1$, and the use of a correction factor (1.35) to account for the dependence of polymeric pigments on pH.

Separation and quantification of monomeric anthocyanins by HPLC

The identification of fourteen individual monomeric anthocyanins was performed using the method and chromatographic conditions described by Roggero *et al.* (1986). Quantification was based on a calibration curve obtained with malvidin 3-*O*-glucoside ($R^2 = 0.981$). Analyses were carried out using an HPLC system (Perkin-Elmer, USA) equipped with a Series 200 pump and an LC95 UV/Visible detector, employing a C18 reversed-phase column (250 mm × 4 mm, 5 µm) protected by a pre-column of the same material, both LichroCart columns supplied by Merck (Germany). The mobile phases consisted of: A (40% formic acid in bidistilled water), B (acetonitrile), and C (bidistilled water). After each run, the column was washed with methanol/water (50:50 v/v). The initial HPLC conditions were 25% A, 6% B, and 69% C for 15 minutes, followed by a linear gradient to 25% A, 25.5% B, and 49.5% C over 70 minutes. The program ended after 20 min under the same solvent composition (25% A, 25.5% B, and 49.5% C). The flow rate was 0.7 mL/min, and detection was carried out at 520 nm. Samples and solvents were filtered under the same conditions, and 20 µL was injected for each run. Wine extracts were previously separated and filtered before injection. All analyses were performed in triplicate.

Separation of proanthocyanidins in Sep-Pak C18 cartridges and quantification of the obtained fractions by the vanillin assay

Flavanols in wine samples were performed using a Sep-Pak C18 cartridge (Waters, USA) according to their degree of polymerisation in three fractions: monomeric (using ethyl ether as solvent), oligomeric (extracted with methanol) and polymeric fractions (extracted with methanol), following the method described by Sun *et al.* (1998a). Flavanol content in each fraction was determined using the vanillin assay (Sun *et al.*, 1998b). Quantification was based on standard curves prepared from flavanol monomers, oligomers, and polymers (Sun *et al.*, 1998a, 1998b; Sun *et al.*, 2001). Separations on the C18 cartridge and the further measurements were performed in triplicate.

Antioxidant activity determination

The antioxidant activity, expressed in millimoles of Trolox equivalents per liter of wine (mM TEAC/L), was analyzed by using two assays with different mechanisms of action: ABTS radical scavenging assay (Re *et al.*, 1999) and DPPH radical scavenging assay (Kim *et al.*, 2002). Trolox was used as standard to construct the calibration curves.

The $ABTS^+$ radical was generated by reacting 7 mM ABTS with 140 mM potassium persulfate at 25 ºC in the dark for 16 h. The solution was diluted in ethanol to an absorbance of 0.700 ± 0.05 at 734 nm. For analysis, 30 µL of sample was mixed with 2970 µL of ABTS solution, and absorbance was read at 734 nm after 6 min.

The DPPH assay was based on the decrease in absorbance at 517 nm. A DPPH solution in ethanol was adjusted to an absorbance of 0.900 ± 0.050. For each sample, 0.1 mL of wine mixed with 2.9 mL of a 100 µM DPPH solution, incubated in the dark for 30 min, and absorbance was measured at 517 nm. All measurements were performed with a Biospectro spectrophotometer (Model SP-220, USA).

Sensorial profile of wines

Sensory analysis was performed by a panel of ten experienced wine tasters (six men and four women, aged 25–50 years) using Quantitative Descriptive Analysis (QDA). A descriptive tasting sheet was developed according to the objectives of the study, and attributes were evaluated on a 10-point unstructured intensity scale, with 0 representing the minimum and 10 the maximum intensity. Color hue was assessed from 0 (purple) to 10 (brown), and overall appreciation from 0 (poor) to 10 (excellent). Tastings were carried out in an acclimatised room maintained at 20 °C, in individual white booths with standardised lighting. Samples (50 mL) were served at 18 ± 2 °C in ISO-standard tasting glasses, coded with random three-digit numbers to ensure anonymity. Each wine was evaluated once by each judge in two sessions: wines from the first and second harvests were assessed in June 2016, and those from the third and fourth harvests in June 2017.

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Statistical analysis

All the physicochemical analyses were made in triplicate. Data were subjected to analysis of variance (ANOVA) and multivariate statistical analyses (principal component analysis, PCA. Differences among treatments were assessed using Tukey's HSD test at a 95% confidence level. All statistical procedures were conducted in R software (R Core Team, 2020).

RESULTS AND DISCUSSION

Yield parameters

Grape quality is influenced by both environmental and genetic factors, and the interaction between these elements is decisive for producing wines with distinctive characteristics. In addition, productivity indices, such as yield per vine or per hectare, exert a direct impact on berry composition, since excessive yields may dilute compounds of oenological relevance and compromise grape quality. In this study, yield per vine was determined in each harvest, based on bunch mass at harvest (kg/vine) (Figure 2).

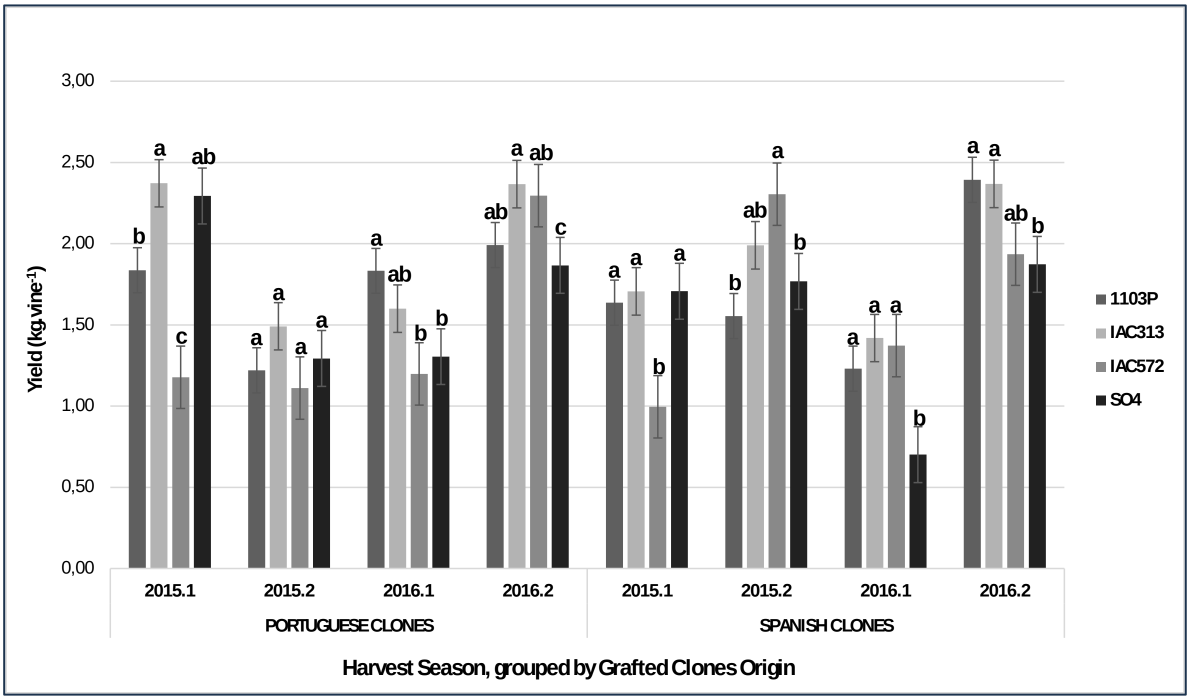

Figure 2. Yield per vine (kg/vine) of Portuguese and Spanish clones, grafted onto four rootstocks, across four consecutive harvests in a tropical semi-arid region of northeastern Brazil. Values represent means ± standard deviation (n = 10). Means within the same column followed by different letters are significantly different according to Tukey's HSD test ($p < 0.05$).

The tropical rootstock 'IAC313' was the only one to consistently maintain higher production levels across all harvests, indicating greater stability under semi-arid tropical conditions. Conversely, the lowest mean yield per vine (1.00 kg/vine) was observed for the 'SO4' in the 2016_1 harvest from Spanish clones, while 'IAC572' showed the lowest yields in the 2015_1 harvest for both Portuguese and Spanish clones. These results reveal a marked variability among rootstocks and harvests, confirming the strong influence of genotype × environment interactions on vine productivity. From a viticultural standpoint, yields below 1.5 kg/vine, such as those recorded in the 2016_1 harvest, reflect the adverse effect of high rainfall and shortened phenological cycle, which limited carbohydrate accumulation. This is consistent with previous reports that low yields under tropical conditions are often associated with climatic stress during ripening (Oliveira *et al.*, 2019b; Figueiredo *et al.*, 2020). On the other hand, the stable and higher yields of 'IAC313' suggest a more efficient adaptation to the semi-arid environment, possibly related to a better water-use efficiency and nutrient uptake, traits previously described for tropical-adapted rootstocks (Carbonneau, 2011; Suriano *et al.*, 2016).

From the oenological perspective, productivity plays a dual role: while moderate yields may promote balanced grape composition and phenolic maturity, excessive productivity tends to dilute sugars, acids, and polyphenols, thereby reducing the structural quality of wines (Santesteban *et al.*, 2023). The yield range observed in this study (1.0 to 2.5 kg/vine) was within a range considered acceptable for maintaining grape quality in warm-climate viticulture. Nevertheless, the sharp yield reductions in the 2016_1 harvest are consistent with the lower alcohol and phenolic concentrations observed in the wines from this vintage, highlighting the close link between productivity, technological ripeness, and wine composition.

Wine classical physicochemical parameters

Table I presents the physicochemical composition of wines produced by blending Portuguese and Spanish clones (*Vitis vinifera* L.) grafted on four rootstocks (‘P1103/Paulsen’, ‘IAC313’, ‘IAC572’, and ‘SO4’) across four consecutive harvests (2015_1, 2015_2, 2016_1, and 2016_2) in a tropical semi-arid climate, in northeast of Brazil. The parameters evaluated included alcohol content, pH, total acidity, volatile acidity, dry extract, and residual sugar. Free and total sulfur dioxide levels complied with Brazilian legislation (≤ 350 mg/L). Production cycles varied from 92 to 122 days, with shorter cycles associated with more pronounced deviations in grape ripening. In warm viticultural areas, accelerated sugar–acid dynamics and phenolic ripening caused by high night-time temperatures and intense solar exposure often hinder balanced grape maturation (Sadras and Moran, 2012; Gordillo *et al.*, 2014; Van Leeuwen and Destrac-Irvine, 2017; Gordillo *et al.*, 2021).

Alcohol content was strongly influenced by harvest date, rootstock, and their interaction. In wines from Portuguese clones, these factors affected alcohol content, pH, and residual sugar, whereas in wines from Spanish clones, all classical parameters were significantly modified. The 2016_2 harvest cycle was shortened due to rainfall and vineyard management decisions. Significant variations were observed in alcohol content ($p < 0.0001$), with the highest values observed in 2015_2 harvest (16.7% for the Portuguese clones grafted on ‘SO4’; 16.6% on ‘IAC572’). In contrast, the lowest levels (< 10%) occurred in 2016_1 across both clones’ origins and all rootstocks, reflecting high rainfall and a shortened 92-day cycle that limited sugar accumulation. These results align with previous findings in the region, where ‘Alicante Bouschet’ wines also showed lower alcohol contents in first semester harvests and higher values in the second semester (Oliveira *et al*., 2020). From the oenological perspective, wines with less than 10% alcohol may compromise structure, mouthfeel, and microbiological stability—critical features for red wines intended for ageing.

Variations in pH values were observed among the different harvests and rootstocks, but no significant differences were detected between the clonal origins. Overall, the pH values were high, ranging from 3.42 to 4.76 for the Portuguese clones and from 3.55 to 4.53 for the Spanish clones. Wines from ‘SO4’ rootstock and from 2016_1 harvest presented the lowest pH values, while ‘IAC572’ consistently resulted in higher pH. High pH is a known trait of tropical wines due to accelerated malic acid degradation under warm conditions. This compromises microbiological stability and freshness, which are critical attributes for red wines (Payan *et al.*, 2023). Comparable results were previously reported for ‘Alicante Bouschet’ and ‘Touriga Nacional’ wines from the São Francisco Valley (Oliveira *et al*., 2019a,b;2020). Recent studies have further demonstrated that rootstock choice can modulate wine pH and buffer acidity: high-vigour rootstocks such as ‘1103P’ and ‘Ramsey’ are associated with higher pH, whereas others like ‘161-49 C’ and ‘420A’ may help maintain acidity, making them strategic for adaptation to climate change (Clingeleffer *et al*., 2022; Santesteban *et al*., 2023; Chen *et al*., 2024b).

Total acidity was also significantly influenced by rootstock and harvest timing. The highest values occurred in the 2016_1 harvest, linked to a shorter cycle, while the lowest values were recorded in 2015_2, associated with extended ripening and malic acid degradation. Total acidity ranged from 4.5 to 11.5 g/L in Portuguese clones and 4.5 to 11.7 g/L in Spanish clones, with the highest levels observed in wines from ‘P1103’ (Portuguese clones) and ‘SO4’ (Spanish clones). These results confirm the importance of rootstock and genotype interactions, as also reported in Mediterranean viticulture (Santesteban *et al.*, 2023). Semester effects were not significant within rootstocks but were evident for Spanish clones, consistent with previous findings that second-semester harvests often result in lower acidity due to greater thermal accumulation and potassium uptake (Figueiredo *et al.*, 2020; Plantevin *et al*., 2024). Notably, ‘SO4’ consistently produced wines with higher acidity and alcohol, supporting previous evidence that this rootstock can moderate vine vigour and improve acid balance in warm climates (Klimek *et al*., 2022).

In all treatments, volatile acidity remained below 1.2 g/L, dry extract above 21.0 g/L, and residual sugar below 4.0 g/L, confirming that the wines met Brazilian standards for dry wines and showed no signs of fermentative or microbiological deviations.

Color, flavonoids, non-flavonoids and global phenolic compounds

Polyphenols are a structurally diverse group of compounds that contribute to the sensory profile and health-related properties of wines. They are generally classified into flavonoids and non-flavonoids (Tzachristas *et al*., 2020). Table II presents the color and phenolic composition of wines from Portuguese and Spanish clones (*Vitis vinifera* L.) grafted onto four rootstocks (‘P1103’, ‘IAC313’, ‘IAC572’, and ‘SO4’) over four consecutive harvests (2015_1, 2015_2, 2016_1, and 2016_2) in a tropical semi-arid climate. The evaluated parameters included color intensity and hue, total phenolics, flavonoids, and non-flavonoids. All variables were significantly affected by rootstock, harvest season, clone origin, and their interactions, confirming the strong influence of genetic background and environment on the phenolic profile and visual profile of wines.

Color intensity varied markedly across harvests and rootstocks ($p < 0.01$). The highest values were recorded in the 2015_2 harvest, particularly for wines from Portuguese clones on ‘SO4’ (18.9) and ‘IAC572’ (17.6). In contrast, values below 5.0 were observed in 2016_1 for both clone origins, indicating reduced pigment concentration or limited extraction.

The enhanced intensity in 2015 harvests is consistent with more advanced grape maturity and favorable radiation and temperature conditions, which promote anthocyanin biosynthesis (Yin *et al*., 2022; Rouxinol *et al*., 2023; Wang *et al*., 2025). The decline in 2016_1 reflects shorter ripening cycles and higher rainfall, which also reduced yield, limiting sugar accumulation and anthocyanin development.

Hue ranged from 0.724 (Portuguese clones grafted onto ‘SO4’, 2016_1) to 1.051 (Portuguese clones on ‘P1103’, 2015_1). Portuguese clones generally showed higher hue values than Spanish clones, suggesting more evolved tonality, often associated with oxidative reactions and premature ageing.

These changes may arise from higher pH, lower acidity, or oxygen exposure during vinification. Significant effects of clone origin, rootstock, and harvest on hue values highlight the role of genotype × environment × rootstock interactions in determining oxidative stability. Similar patterns have been reported in Mediterranean wines, where high vigour and alkaline conditions accelerate pigment polymerisation (Oliveira *et al*., 2024).

Total phenolics were strongly influenced by harvest and rootstock ($p < 0.0001$), Portuguese clones ranged from 1,035.1 mg/L (‘SO4’) to 1260.5 mg/L (‘IAC313’), while Spanish clones ranged from 1227.1 mg/L (‘SO4’) to 1725.5 mg/L (‘IAC313’). Declines in phenolics were linked to lower light incidence and reduced phenylpropanoid pathway activation, as previously described by Cataldo *et al*. (2023).

Table I

Classical analyses in Portuguese and Spanish clones’ wines from grapes produced in tropical semi-arid region in Brazilian northeastern, from four consecutive harvests

Rootstock	**Harvest**	**Physicochemical composition**											
		Wines from Portuguese Clones						**Wines from Spanish Clones**					
		Alcohol content (%, v/v)	**pH**	**Total acidity (g/L)**	**Volatile acidity (g/L)**	**Dry extract (g/L)**	**Residual sugar (g/L)**	**Alcohol content (%, v/v)**	**pH**	**Total acidity (g/L)**	**Volatile acidity (g/L)**	**Dry extract (g/L)**	**Residual sugar (g/L)**
‘P1103’	**2015_1**	13.9^{d} ±0.3	4.51^{cd} ±0.01	4.5^{j} ±0.0	0.63^{a} ±0.00	39.6^{b} ±0.9	2.2^{d} ± 0.1	15.5^{cd} ±0.0	4.38^{d} ±0.00	6.9^{e} ±0.0	0.39^{e} ±0.00	47.4^{a} ±0.1	3.2^{a} ±0.0
	2015_2	16.2^{b} ±0.0	4.47^{de} ±0.01	5.4^{g} ±0.1	0.45^{e} ±0.01	42.6^{a} ±0.1	3.1^{a} ±0.0	15.5^{cd} ±0.0	4.42^{b} ±0.00	5.1^{j} ±0.0	0.44^{d} ±0.00	36.7^{cd} ±0.0	2.3^{e} ±0.0
	2016_1	9.6^{g} ±0.0	3.55^{j} ±0.00	11.5^{a} ±0.1	0.21^{k} ±0.00	35.8^{c} ±0.0	0.4^{g} ±0.0	9.5^{g} ±0.1	3.77^{j} ±0.01	9.8^{d} ±0.1	0.27^{i} ±0.00	34.6^{fg} ±0.4	0.5^{i} ±0.0
	2016_2	12.8^{e} ±0.4	4.23^{g} ±0.00	6.0^{e} ±0.0	0.37^{g} ±0.01	32.9^{ef} ±1.4	1.4^{f} ±0.0	12.2^{f} ±0.1	4.31^{f} ±0.00	5.4^{h} ±0.0	0.37^{e} ±0.01	28.4^{ij} ±0.4	1.5^{g} ±0.1
‘IAC313’	**2015_1**	13.7^{d} ±0.0	4.50^{cd} ±0.00	4.6^{ij} ±0.1	0.51^{d} ±0.00	35.1^{cd} ±0.3	2.0^{de} ±0.1	14.7^{e} ±0.5	4.53^{a} ±0.00	4.6^{l} ±0.1	0.57^{b} ±0.00	38.2^{c} ±1.5	2.7^{c} ±0.0
	2015_2	14.0^{d} ±0.0	4.42^{e} ±0.02	4.7^{i} ±0.0	0.43^{b} ±0.01	31.7^{f} ±0.3	2.8^{b} ±0.1	15.9^{bc} ±0.0	4.31^{fg} ±0.00	5.0^{k} ±0.0	0.38^{e} ±0.01	36.4^{de} ±0.1	2.5^{d} ±0.0
	2016_1	8.5^{h} ±0.0	3.57^{j} ±0.00	11.3^{b} ±0.0	0.33^{i} ±0.01	32.9^{ef} ±0.1	0.4^{g} ±0.0	9.3^{g} ±0.1	3.62^{l} ±0.00	10.6^{c} ±0.1	0.35^{f} ±0.01	32.1^{h} ±0.3	0.6^{i} ±0.0
	2016_2	12.2^{f} ±0.0	4.09^{h} ±0.09	6.0^{e} ±0.0	0.35^{h} ±0.00	29.9^{g} ±0.0	1.4^{f} ±0.1	12.3^{f} ±0.1	4.30^{g} ±0.00	5.1^{j} ±0.0	0.33^{g} ±0.01	27.4^{j} ±0.5	1.5^{g} ±0.0
‘IAC572’	**2015_1**	14.5^{c} ±0.0	4.76^{a} ±0.01	4.7^{i} ±0.1	0.62^{a} ±0.00	42.4^{a} ±0.1	2.0^{de} ±0.1	15.1^{de} ±0.0	4.39^{d} ±0.01	6.5^{f} ±0.0	0.39^{e} ±0.00	42.0^{b} ±0.0	3.0^{b} ±0.0
	2015_2	16.6^{ab} ±0.0	4.67^{b} ±0.00	5.1^{h} ±0.2	0.59^{b} ±0.01	31.7^{f} ±0.3	2.5^{c} ±0.0	16.2^{ab} ±0.0	4.42^{b} ±0.00	4.5^{l} ±0.0	0.66^{a} ±0.01	34.7^{efg} ±0.1	2.1^{f} ±0.0
	2016_1	9.2^{g} ±0.1	3.77^{i} ±0.00	9.3^{c} ±0.0	0.42^{f} ±0.00	33.3^{e} ±0.2	0.5^{g} ±0.1	9.3^{g} ±0.4	3.75^{k} ±0.00	10.7^{b} ±0.1	0.30^{h} ±0.00	33.6^{gh} ±1.4	0.5^{i} ±0.1
	2016_2	13.0^{e} ±0.2	4.32^{f} ±0.00	5.7^{f} ±0.0	0.35^{hi} ±0.01	33.7^{de} ±0.7	1.4^{f} ±0.1	12.6^{f} ±0.2	4.40^{c} ±0.00	5.6^{g} ±0.0	0.35^{f} ±0.00	29.0^{ij} ±0.5	1.4^{g} ±0.0
‘SO4’	**2015_1**	13.6^{d} ±0.1	4.41^{e} ±0.01	4.6^{ij} ±0.1	0.58^{b} ±0.00	35.0^{cd} ±0.4	1.8^{e} ±0.0	15.5^{cd} ±0.0	4.21^{h} ±0.00	6.4^{f} ±0.1	0.35^{fg} ±0.01	40.5^{b} ±0.0	3.0^{ab} ±0.1
	2015_2	16.7^{a} ±0.0	4.56^{c} ±0.01	5.6^{fg} ±0.0	0.54^{c} ±0.01	41.4^{a} ±0.1	3.0^{ab} ±0.0	16.7^{a} ±0.1	4.19^{i} ±0.00	5.3^{i} ±0.0	0.47^{c} ±0.01	37.6^{cd} ±0.1	2.6^{c} ±0.0
	2016_1	9.2^{g} ±0.1	3.46^{k} ±0.00	11.3^{b} ±0.0	0.28^{j} ±0.01	32.9^{ef} ±0.5	0.5^{g} ±0.1	9.6^{g} ±0.1	3.55^{m} ±0.00	11.7^{a} ±0.0	0.18^{j} ±0.01	36.1^{de} ±0.4	0. 7^{h} ±0.0
	2016_2	12.1^{f} ±0.1	4.16^{gh} ±0.00	6.4^{d} ±0.1	0.34^{hi} ±0.01	29.9^{g} ±0.1	1.4^{f} ±0.0	12.6^{f} ±0.1	4.35^{e} ±0.00	5.6^{g} ±0.0	0.35^{fg} ±0.01	29.6^{i} ±0.2	1.5^{g} ±0.1
Rootstock *per* harvest	***Sig.***	***	***	***	***	***	***	***	***	***	***	***	***
Harvest date	***Sig.***	***	***	***	***	***	***	***	***	***	***	***	***
Rootstock *vs* harvest	***Sig.***	***	***	***	***	***	***	***	***	***	***	***	***
Rootstock *per* semester	***Sig.***	ns	ns	Ns	ns	**	ns	ns	ns	ns	ns	ns	***
Semester	***Sig.***	***	*	Ns	ns	ns	***	*	***	**	*	***	***
Rootstock *vs* semester	***Sig.***	ns	ns	Ns	ns	ns	ns	ns	ns	ns	**	ns	***
Cultivar	***Sig.***		**Alcohol content (%, v.v^{-1}):** ***			**pH:** ns			**Total acidity (g.L^{-1}):** ns				

Means within the same column followed by different letters are significantly different according to the Tukey test ($p< 0.05$); ns: not significant; * significant differences at 95% confidence level; ** significant differences at 99.9% confidence level; *** significant differences at 99.99% confidence level. Harvest: 2015_1 (1st semester of 2015); 2015_2 (2nd semester of 2015); 2016_1 (1st semester of 2016); 2016_2 (2nd semester of 2016). Total acidity is expressed as tartaric acid equivalents. Volatile acidity is expressed as acetic acid equivalents.

Table II

Color and phenolic compounds in wines from Portuguese and Spanish clones of grapes produced in tropical semi-arid region in Brazilian northeastern, from four consecutive harvests

Rootstock	Harvest	Color and global phenolic composition									
		Wines from Portuguese Clones					Wines from Spanish Clones				
		Color intensity (a.u. x 10)	**Color** hue **(a.u.)**	**Total phenols (mg/L)**	**Flavonoids (mg/L)**	**Non-flavonoids (mg/L)**	**Color intensity (a.u. x 10)**	**Color** hue **(a.u.)**	**Total phenols (mg/L)**	**Flavonoids (mg/L)**	**Non-flavonoids (mg/L)**
‘P1103’	**2015_1**	14.0^{g} ±0.020	1.051^{a} ±0.001	2709.3^{bc} ±14.1	2617.9^{bc} ±11.7	91.4^{cd} ±2.8	18.0^{b} ±0.020	1.033^{a} ±0.000	3079.3^{ab} ±42.2	2985.4^{a} ±36.2	93.9^{ab} ±6.3
	2015_2	19.9^{a} ±0.012	0.946^{e} ±0.000	3079.3^{a} ±59.7	2981.8^{a} ±62.9	97.5^{bc} ±3.5	15.2^{f} ±0.017	0.923^{e} ±0.000	2549.6^{d} ±13.1	2465.2^{d} ±15.5	84.5^{bcde} ±4.1
	2016_1	3.6^{n} ±0.032	0.806^{k} ±0.005	1134.3^{h} ±10.4	1048.7^{i} ±10.1	85.7^{defg} ±2.8	5.3^{l} ±0.015	0.778^{j} ±0.007	1530.2^{j} ±9.9	1453.5^{i} ±10.3	76.7^{ef} ±0.5
	2016_2	9.4^{j} ±0.027	0.842^{i} ±0.001	2051.2^{e} ±24.3	1974.0^{f} ±25.4	77.2^{gh} ±1.2	9.2^{j} ±0.006	0.825^{h} ±0.001	1920.7^{gh} ±19.0	1827.5^{gh} ±21.9	93.2^{ab} ±4.8
‘IAC313’	**2015_1**	13.2^{h} ±0.071	0.975^{d} ±0.001	2425.6^{d} ±28.3	2346.3^{e} ±23.8	79.3^{fgh} ±6.3	15.2^{f} ±0.102	1.020^{b} ±0.011	2757.8^{c} ±11.7	2669.1^{c} ±12.5	88.7^{abcd} ±4.0
	2015_2	14.4^{e} ±0.015	0.929^{f} ±0.001	2416.9^{d} ±19.0	2325.8^{e} ±17.7	91.2^{cd} ±1.5	14.9^{g} ±0.012	0.913^{e} ±0.000	2506.5^{de} ±59.9	2426.6^{de} ±60.3	79.8^{def} ±1.7
	2016_1	3.4^{o} ±0.012	0.808^{k} ±0.003	1035.1^{i} ±14.6	929.6^{j} ±13.8	105.5^{ab} ±0.8	4.3^{n} ±0.017	0.728^{k} ±0.001	1227.1^{k} ±3.2	1136.7^{j} ±1.3	90.4^{abcd} ±2.2
	2016_2	8.8^{l} ±0.006	0.822^{j} ±0.001	1850.6^{f} ±13.1	1765.8^{g} ±11.8	84.8^{defg} ±1.3	8.4^{k} ±0.015	0.813^{i} ±0.001	1781.6^{hi} ±26.2	1689.1^{h} ±24.8	92.5^{abc} ±1.8
‘IAC572’	**2015_1**	15.6^{d} ±0.026	1.035^{b} ±0.000	2637.0^{c} ±16.3	2536.2^{d} ±13.7	100.8^{b} ±2.6	17.8^{c} ±0.047	1.031^{a} ±0.002	2907.8^{bc} ±14.6	2808.8^{bc} ±11.1	98.9^{a} ±4.5
	2015_2	17.6^{c} ±0.023	0.987^{c} ±0.001	2743.8^{b} ±40.5	2657.4^{b} ±39.0	86.4^{def} ±1.8	16.7^{e} ±0.040	0.935^{d} ±0.001	2358.7^{e} ±74.2	2275.3^{e} ±22.9	83.4^{bcdef} ±6.0
	2016_1	4.5^{m} ±0.021	0.781^{l} ±0.003	1058.8^{hi} ±18.0	948.1^{j} ±17.6	110.7^{a} ±2.2	4.8^{m} ±0.026	0.769^{j} ±0.001	1391.1^{jk} ±14.6	1309.9^{i} ±13.4	81.1^{cdef} ±1.2
	2016_2	9.1^{k} ±0.025	0.889^{h} ±0.002	1851.7^{f} ±18.0	1761.2^{g} ±14.3	90.5^{cde} ±3.9	9.8^{i} ±0.010	0.879^{f} ±0.001	1967.1^{g} ±8.1	1878.0^{g} ±9.3	89.1^{abcd} ±2.1
‘SO4’	**2015_1**	14.2^{f} ±0.012	0.987^{c} ±0.001	2639.2^{c} ±29.4	2557.6^{cd} ±27.8	81.6^{efg} ±1.9	16.9^{d} ±0.023	0.969^{c} ±0.001	3055.6^{ab} ±25.7	2967.9^{ab} ±29.5	87.7^{abcde} ±4.4
	2015_2	18.9^{b} ±0.067	0.923^{g} ±0.001	3061.0^{a} ±32.4	2978.6^{a} ±26.5	82.3^{defg} ±6.5	20.1^{a} ±0.049	0.855^{g} ±0.005	3174.2^{a} ±26.0	3101.4^{a} ±25.1	72.8^{f} ±2.5
	2016_1	4.4^{m} ±0.017	0.724^{m} ±0.001	1260.5^{g} ±19.5	1188.2^{h} ±20.4	72.3^{h} ±1.3	5.4^{l} ±0.006	0.824^{h} ±0.002	1725.5^{i} ±12.9	1666.0^{h} ±13.3	59.4^{g} ±0.6
	2016_2	9.6^{i} ±0.023	0.807^{k} ±0.003	2004.9^{e} ±23.0	1922.1^{f} ±24.9	82.7^{defg} ±2.0	10.5^{h} ±0.010	0.822^{hi} ±0.001	2177.5^{f} ±4.9	2094.2^{f} ±7.9	83.3^{bcdef} ±4.7
Rootstock *per* harvest	***Sig.***	***	***	***	***	***	***	***	***	***	***
Harvest date	***Sig.***	***	***	***	***	***	***	***	***	***	***
Rootstock *vs* harvest	***Sig.***	***	***	***	***	***	***	***	***	***	***
Rootstock *per* semester	***Sig.***	ns	ns	ns	ns	ns	ns	ns	ns	ns	***
Semester	***Sig.***	**	ns	*	*	ns	ns	ns	ns	ns	**
Rootstock *vs* semester	***Sig.***	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Cultivar	***Sig.***	**Colour intensity:**	**	**Color** hue**:**	*	**Total phenols:**	***	**Flavonoids:**	***	**Non-flavonoids:**	**

Means within the same column followed by different letters are significantly different according to the Tukey test ($p< 0.05$); ns: not significant; * significant differences at 95% confidence level; ** significant differences at 99.9% confidence level; *** significant differences at 99.99% confidence level; Harvest: 2015_1 (1st semester of 2015); 2015_2 (2nd semester of 2015); 2016_1 (1st semester of 2016); 2016_2 (2nd semester of 2016). a.u. (absorbance unit, measured at 520 nm). Total phenols, flavonoids and non-flavonoids expressed as gallic equivalents.

Flavonoids were higher in wines from Portuguese clones harvested in the second semester, in line with the climatic pattern of greater thermal amplitude, solar radiation, and moderate water deficit. This agrees with Oliveira *et al*. (2018) for 'Touriga Nacional' wines and with recent studies linking UV-B radiation and water stress to increased expression of flavonoid-related genes (Singh *et al*., 2023; Sun *et al*., 2023; Hidalgo-Sanz *et al*., 2023; Shi *et al*., 2024).

In contrast, non-flavonoids were more stable across seasons in Spanish clones, with only moderate variations among rootstocks. 'SO4' and 'P1103' consistently enhanced phenolic potential, particularly in 2015_1 and 2015_2, suggesting rootstock-driven modulation of vigour and berry composition. In Portuguese clones, non-flavonoid peaks occurred with 'IAC572' (110.7 mg/L) and 'IAC313' (105.5 mg/L) in 2015_2, whereas Spanish clones showed higher levels in 2015_1 harvest across all rootstocks (Table II).

In summary, wines from 2015_2 harvest expressed the most favourable phenolic and color profile, especially Spanish clones onto 'SO4'. Conversely, 2016_1 was characterised by reduced color intensity and flavonoid content, linked to low yields, short cycles, and rainfall stress. However, non-flavonoid stability across treatments suggests that an antioxidant buffer may mitigate phenolic losses. From the oenological perspective, these results reinforce the importance of selecting clone–rootstock combinations adapted to tropical semi-arid conditions to optimise pigment retention, phenolic maturity, and long-term color stability.

Total anthocyanins and other pigments

The analysis of total anthocyanins (Table III) revealed significant variation among treatments, reflecting the strong influence of seasonal factors and the combination of clone-rootstock combinations on wine phenolic composition. Concentrations ranged from 21.0 mg/L in Portuguese clones grafted onto 'IAC313' during the 2016_1 harvest to 234.4 mg/L in Spanish clones grafted onto 'SO4' during the 2016_2 harvest.

This wide range highlights the sensitivity of anthocyanin accumulation to edaphoclimatic conditions and vineyard management, particularly grape maturity at harvest. The markedly low levels observed in 2016_1 suggest that grapes harvested during this cycle were less advanced in phenolic ripening, likely due to rainfall and the shortened 92-day cycle that also reduced yield. These conditions limited both sugar accumulation and anthocyanin synthesis, consistent with previous reports linking pigment concentration to berry maturity, must pH, temperature, and light exposure (Yin *et al*., 2022; Rouxinol *et al*., 2023). These results are consistent with observations from other viticultural regions. In Valencia, Buesa *et al*. (2021) reported anthocyanins concentrations of 255.7–618.5 mg/L in 'Tempranillo' wines from winter pruning and 292.8–697.5 mg/L from late pruning, showing higher pigment accumulation under delayed harvest. In the São Francisco Valley, Oliveira *et al*. (2020), found total anthocyanin contents in 'Touriga Nacional' ranging from 381.7 to 713.9 mg/L in first-semester wines and 453.2 to 626.0 mg/L in second-semester wines. Likewise, 'Syrah' wines grafted onto 'IAC313' and 'P1103' presented values of 190.8–316.5 mg/L and 205.8–375.6 mg/L respectively, with a clear semester effect and greater polymerisation in the second semester (Oliveira *et al*., 2019a). These comparisons show that the anthocyanin concentrations obtained in the present study were considerably lower, particularly in 2016_1, indicating a strong climatic limitation under certain tropical conditions.

Genetic and rootstock effects also played an important role. Spanish clones, especially when grafted onto 'SO4', consistently achieved higher anthocyanin levels under favourable harvests, suggesting more efficient activation of pigmentation-related genes and improved extraction during winemaking. Rootstock physiology likely modulated water and nutrient uptake, influencing pigment biosynthesis and stability.

From the oenological perspective, the low anthocyanin concentrations recorded in 2016_1 compromise color density, oxidative stability, and ageing potential. Conversely, the higher values obtained in 2016_2 and 2015_2 reinforce the importance of aligning harvest timing and rootstock choice to maximise pigment expression in tropical wines. These findings underscore the need for targeted viticultural strategies, such as adjusting pruning dates, managing canopy microclimate, and optimising harvest scheduling, to mitigate seasonal variability and enhance phenolic quality under semi-arid tropical conditions.

Polymeric and other coloured pigments varied significantly according to harvest season, clone, and rootstock (Table III). The highest concentrations recorded in the 2015_2 and 2016_2 harvests, showing a positive correlation with total anthocyanin content. These pigments are crucial for wine color stability during ageing, as they originate from condensation reactions between anthocyanins and flavan-3-ols, either directly or via acetaldehyde, forming stable ethyl-linked structures. High levels in wines from Spanish clones grafted onto 'SO4' rootstock during favourable harvests suggest greater potential for long-term color preservation and improved sensory attributes associated with intensity and saturation. These polymerisation and copigmentation processes contribute significantly to maintaining color and sensory quality in red wines during maturation (Zhao *et al*., 2022; Zhao *et al*., 2023). In contrast, 2016_1 showed reduced polymeric pigment formation, consistent with the lower anthocyanin concentrations. This reduction likely reflects incomplete polymerisation due to limited precursor availability and less efficient extraction under suboptimal ripening conditions.

Copigmentation and polymerisation indices were also significantly affected by the clone × rootstock × harvest interaction ($p < 0.01$), underscoring the complexity of phenolic transformations. Higher copigmentation indices were typically found in wines from second-semester harvests, particularly Portuguese clones grafted onto 'IAC572' and 'SO4', suggesting enhanced formation of anthocyanins in complexed forms that protect against oxidation. Polymerisation indices followed a similar pattern, with higher values indicating more advanced pigment stabilization and improved ageing potential.

The influence of environmental factors on anthocyanin and tannin dynamics has been well documented. For instance, in 'Touriga Nacional' grapes, anthocyanins increase until harvest maturity (Rouxinol *et al*., 2023), but rainfall and shortened cycles–as seen in 2016_1—can disrupt this accumulation, limiting subsequent polymerization. These results caution against attributing superior phenolic expression solely to harvest timing; grape maturity, climatic conditions, and rootstock physiology strongly modulate the extent of polymerisation and copigmentation.

From the oenological perspective, wines from 2015_2 and 2016_2, with higher copigmentation indices and polymeric pigment content, present greater potential for color stability and longevity. Conversely, the wines from 2016_1, characterised by low anthocyanins and reduced pigment transformation, may exhibit weaker color retention and faster oxidative evolution. Previous studies confirm that both grape composition and vinification practices, such as oxygen management and maceration conditions, strongly influence pigment stabilisation (Fan *et al*., 2019; Gordillo *et al*., 2021; Zhang *et al*., 2022).

In summary, the stability of wine color under tropical semi-arid conditions is strongly influenced by seasonal variability, with second-semester harvests enabling more favourable phenolic accumulation and transformation. Clone–rootstock combinations, particularly highlight the importance of integrating vineyard management, harvest timing, and tailored winemaking practices to mitigate climatic limitations and secure long-term color quality in tropical wines.

Condensed tannins, tanning power and antioxidant capacity

Table IV summarises tannins, tanning power, and antioxidant capacity in tropical wines produced from Portuguese and Spanish

Table III

Total anthocyanins and other pigments in wines from Portuguese and Spanish clones of grapes produced in tropical semi-arid region in Brazilian northeastern, from four consecutive harvests

Rootstock	Harvest	Total anthocyanins and other pigments													
		Wines from Portuguese Clones							Wines from Spanish Clones						
		Total anthocyanins (mg/L)	**Coloured anthocyanins (mg/L)**	**Ionization index (%)**	**Total pigments (a.u.)**	**Polymeric pigments (a.u.)**	**Polymeric pigments index (%)**	**Copigmentation (%)**	**Total anthocyanins (mg/L)**	**Coloured anthocyanins (mg/L)**	**Ionization index (%)**	**Total pigments (a.u.)**	**Polymeric pigments (a.u.)**	**Polymeric pigments index (%)**	**Copigmentation (%)**
‘P1103’	**2015_1**	132.9^{f} ±4.4	27.4^{g} ±1.6	20.6^{defg} ±0.6	14.3^{ef} ±0.1	4.6^{e} ±0.1	32.1^{c} ±0.7	60.2^{cde} ±0.2	157.2^{efg} ±11.1	36.0^{de} ±1.7	22.9^{efg} ±1.1	17.6^{b} ±0.5	5.9^{b} ±0.1	33.2^{bcd} ±1.2	59.5^{ef} ±0.3
	2015_2	181.6^{cd} ±3.2	45.9^{a} ±1.8	25.3^{c} ±0.5	19.8^{a} ±0.0	6.4^{a} ±0.1	32.5^{c} ±0.5	59.6^{de} ±0.2	149.4^{fg} ±7.2	39.9^{cd} ±2.9	26.8^{cdef} ±2.4	15.5^{cd} ±0.4	4.8^{ef} ±0.1	31.0^{cd} ±0.8	59.5^{ef} ±0.2
	2016_1	35.0^{g} ±1.5	11.1^{i} ±0.6	31.7^{b} ±3.1	3.8^{gh} ±0.1	1.3^{j} ±0.0	32.7^{c} ±0.5	61.9^{b} ±0.8	44.1^{h} ±2.6	15.1^{fg} ±0.4	34.2^{bc} ±1.4	5.4^{e} ±0.1	1.9^{ij} ±0.0	35.6^{b} ±0.9	60.1^{de} ±0.0
	2016_2	194.1^{bc} ±1.9	38.9^{e} ±0.8	20.0^{efg} ±0.5	13.8^{f} ±0.2	2.4^{g} ±0.0	17.7^{f} ±0.2	63.1^{a} ±0.3	216.8^{abc} ±1.0	38.6^{cde} ±0.2	17.8^{g} ±0.2	14.9^{d} ±0.1	2.4^{h} ±0.0	16.3^{f} ±0.0	63.1^{ab} ±0.2
‘IAC313’	**2015_1**	154.1^{e} ±5.7	33.2^{f} ±0.8	21.6^{cdef} ±1.3	14.6^{ef} ±0.3	4.2^{f} ±0.0	28.4^{de} ±0.4	60.2^{cde} ±0.2	141.1^{g} ±7.8	34.2^{e} ±0.9	24.3^{defg} ±0.9	15.1^{cd} ±0.3	4.8^{de} ±0.0	32.0^{cd} ±1.0	59.7^{ef} ±0.4
	2015_2	176.3^{cd} ±5.9	42.1^{cd} ±0.9	23. 9^{cde} ±0.3	16.0^{c} ±0.2	4.3^{f} ±0.1	26.9^{e} ±0.7	60.4^{cd} ±0.3	172.3^{def} ±11.4	42.0^{bc} ±1.5	24.4^{defg} ±1.6	16.2^{c} ±0.6	4.6^{f} ±0.1	28.2^{e} ±1.1	59.6^{ef} ±0.3
	2016_1	21.0^{g} ±1.2	8.2^{j} ±0.2	39.2^{a} ±2.3	3.2^{h} ±0.1	1.3^{j} ±0.0	40.3^{a} ±0.8	59.7^{de} ±0.4	26.5^{h} ±4.5	11.1^{g} ±0.2	42.9^{a} ±7.5	4.1^{f} ±0.2	1.7^{k} ±0.0	40.6^{a} ±2.3	59.2^{f} ±0.3
	2016_2	203.2^{ab} ±4.3	40.1^{de} ±0.2	19.8^{fg} ±0.4	13.8^{f} ±0.2	2.2^{h} ±0.0	15.7^{g} ±0.3	63.3^{a} ±0.2	229.1^{a} ±2.5	38.8^{cde} ±0.4	16.9^{g} ±0.1	14.8^{d} ±0.1	2.0^{i} ±0.0	13.7^{f} ±0.2	63.9^{a} ±0.3
‘IAC572’	**2015_1**	154.3^{e} ±1.4	32.1^{f} ±0.8	20.8^{defg} ±0.7	16.1^{c} ±0.2	5.0^{d} ±0.1	31.3^{c} ±0.0	59.8^{de} ±0.1	165.6^{efg} ±12.2	38.2^{cde} ±3.3	23.1^{efg} ±2.3	17.7^{b} ±0.6	5.6^{bc} ±0.2	31.9^{cd} ±1.2	59.8^{def} ±0.2
	2015_2	190.0^{bc} ±19.7	42.5^{bcd} ±0.8	22.5^{cdef} ±2.5	18.6^{b} ±1.0	5.4^{c} ±0.0	29.3^{d} ±1.5	59.7^{de} ±0.3	194.8^{cd} ±11.0	46.3^{b} ±0.3	23.8^{efg} ±1.4	18.2^{b} ±0.5	5.1^{d} ±0.0	27.9^{e} ±0.9	59.6^{ef} ±0.2
	2016_1	38.1^{g} ±0.5	11.5^{hi} ±0.1	30.2^{b} ±0.2	4.6^{g} ±0.0	1.6^{i} ±0.0	35.4^{b} ±0.3	59.4^{e} ±0.4	44.7^{h} ±4.0	14.3^{fg} ±0.2	32.1^{bcd} ±3.3	5.2^{ef} ±0.2	1.8^{jk} ±0.0	34.0^{bc} ±1.3	60.6^{d} ±0.2
	2016_2	201.8^{ab} ±2.4	34.4^{f} ±0.7	17.0^{g} ±0.2	14.1^{ef} ±0.1	2.4^{g} ±0.0	17.1^{fg} ±0.3	61.5^{b} ±0.6	223.1^{ab} ±4.7	38.3^{cde} ±0.3	17.2^{g} ±0.4	15.4^{cd} ±0.3	2.6^{gh} ±0.0	16.6^{f} ±0.2	62.8^{b} ±0.2
‘SO4’	**2015_1**	163.0^{de} ±8.3	34.2^{f} ±1.4	21.0^{def} ±0.6	15.6^{cd} ±0.3	4.5^{e} ±0.1	28.7^{de} ±1.0	60.1^{cde} ±0.1	178.6^{de} ±10.0	39.1^{cd} ±2.9	21.9^{efg} ±1.6	18.0^{b} ±0.5	5.5^{c} ±0.1	30.3^{de} ±1.1	60.0^{de} ±0.2
	2015_2	188.0^{bc} ±1.8	45.2^{ab} ±1.2	24.0^{cd} ±0.5	19.6^{a} ±0.1	6.1^{b} ±0.1	31.3^{c} ±0.3	59.9^{de} ±0.1	197.9^{bcd} ±19.0	56.6^{a} ±1.7	28.7^{cde} ±2.0	20.6^{a} ±0.8	6.4^{a} ±0.1	31.2^{cde} ±1.7	59.2^{f} ±0.1
	2016_1	35.6^{g} ±0.9	14.1^{h} ±0.1	39.6^{a} ±0.8	4.5^{g} ±0.1	1.6^{i} ±0.0	36.4^{b} ±0.3	61.1^{bc} ±0.3	49.4^{h} ±5.6	18.7^{f} ±0.2	38.2^{ab} ±4.2	5.4^{e} ±0.3	1.8^{jk} ±0.0	32.7^{bcd} ±1.6	62.0^{c} ±0.4
	2016_2	219.6^{a} ±5.4	44.4^{abc} ±0.2	20.2^{defg} ±0.4	14.9^{de} ±0.3	2.4^{g} ±0.0	15.8^{g} ±0.3	63.6^{a} ±0.2	234.4^{a} ±3.1	44.9^{b} ±0.5	19.1^{fg} ±0.3	16.2^{c} ±0.2	2.7^{g} ±0.0	16.6^{f} ±0.2	63.1^{ab} ±0.2
Rootstock *per* harvest	***Sig.***	***	***	***	***	***	**	***	***	***	*	***	***	**	***
Harvest date	***Sig.***	***	***	***	***	***	***	***	***	***	***	***	***	***	***
Rootstock *vs* harvest	***Sig.***	***	***	***	***	***	***	***	***	***	*	***	***	***	***
Rootstock *per* semester	***Sig.***	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Semester	***Sig.***	***	**	***	***	ns	***	**	***	***	***	***	ns	***	**
Rootstock *vs* semester	***Sig.***	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Cultivar	***Sig.***	**Total anthocyanins**	***	**Colored anthocyanins**	***	**Ionization index**	ns	**Total pigments**	***	**Polymeric pigments**	**	**Polym. pig. index**	ns	**Copigm.**	ns

Means within the same column followed by different letters are significantly different according to the Tukey test ($p< 0.05$); ns: not significant; * significant differences at 95% confidence level; ** significant differences at 99.9% confidence level; *** significant differences at 99.99% confidence level; Harvest: 2015_1 (1st semester of 2015); 2015_2 (2nd semester of 2015); 2016_1 (1st semester of 2016); 2016_2 (2nd semester of 2016). a.u. (absorbance unit). Total and coloured anthocyanins are expressed as malvidin-3-monoglucoside equivalents.

Table IV

Condensed tannins, tanning power and antioxidant capacity in wines from Portuguese and Spanish clones of grapes produced in tropical semi-arid region in Brazilian northeastern, from four consecutive harvests

Rootstock	**Harvest**	**Wines from Portuguese Clones**							**Wines from Spanish Clones**						
		Flavan-3-ols / Condensed tannins (mg/L)				**Tanning power (NTU/mL)**	**Antioxidant capacity (TEAC mMTrolox/L)**		**Flavan-3-ols / Condensed tannins (mg/L)**				**Tanning Power (NTU/mL)**	**Antioxidant capacity (TEAC mMTrolox/L)**	
		Monomeric	**Oligomeric**	**Polymeric**	**Total tannins**		**ABTS**	**DPPH**	**Monomeric**	**Oligomeric**	**Polymeric**	**Total tannins**		**ABTS**	**DPPH**
‘P1103’	**2015_1**	16.2^{abcd} ±1.4	41.7^{bc} ±1.3	1586.5^{bc} ±67.6	1644.4^{bc} ±67.7	241.0^{abcd} ±4.7	17.9^{e} ±0.1	12.3^{g} ±0.0	19.2^{a} ±0.3	63.8^{b} ±3.8	1716.2^{cd} ±29.7	1799.2^{cde} ±26.2	273.3^{a} ±1.4	18.3^{e} ±0.1	12.1^{gh} ±0.1
	2015_2	14.6^{de} ±0.5	47.2^{ab} ±6.5	1491.0^{cdef} ±55.4	1552.7^{cdef} ±49.4	263.0^{ab} ±1.4	36.7^{a} ±1.4	24.6^{b} ±0.2	13.3^{def} ±0.8	40.2^{e} ±7.2	1616.2^{cd} ±81.1	1669.7^{e} ±74.7	229.1^{ab} ±5.9	29.8^{bc} ±0.6	22.5^{c} ±0.3
	2016_1	6.9^{f} ±0.5	16.2^{d} ±1.6	1340.5^{fg} ±33.8	1363.7^{g} ±31.7	246.5^{abc} ±3.9	13.0^{f} ±1.5	11.7^{hi} ±0.2	5.6^{g} ±0.2	15.7^{fg} ±2.0	1400.9^{ef} ±6.1	1422.3^{f} ±8.2	177.0^{b} ±4.8	17.7^{ef} ±0.4	16.5^{f} ±0.0
	2016_2	13.5^{e} ±0.2	45.7^{ab} ±0.8	1346.9^{fg} ±75.0	1406.1^{efg} ±75.7	173.4^{e} ±8.6	28.1^{d} ±0.1	16.8^{f} ±0.1	11.8^{ef} ±1.8	46.4^{de} ±7.1	1389.2^{ef} ±14.9	1447.4^{f} ±9.6	225.9^{ab} ±3.2	26.7^{d} ±0.2	17.8^{e} ±0.3
‘IAC313’	**2015_1**	15.9^{abcde} ±1.4	42.0^{bc} ±0.4	1709.9^{ab} ±41.9	1767.8^{ab} ±43.7	208.5^{bcde} ±1.3	16.5^{e} ±0.0	11.3^{i} ±0.0	19.3^{a} ±0.5	49.3^{cde} ±3.3	1888.3^{b} ±68.9	1956.8^{b} ±65.2	224.3^{ab} ±3.1	16.1^{f} ±0.1	12.3^{gh} ±0.1
	2015_2	13.9^{de} ±1.4	39.8^{bc} ±4.8	1548.6^{bcd} ±67.6	1602.3^{bc} ±70.9	237.5^{abcd} ±4.6	28.7^{cd} ±1.2	20.7^{d} ±0.0	14.6^{cd} ±0.5	48.2^{de} ±3.2	1707.2^{cd} ±71.6	1770.0^{de} ±69.1	196.6^{ab} ±3.1	31.4^{ab} ±0.1	23.3^{c} ±0.2
	2016_1	5.4^{fg} ±0.1	11.4^{d} ±0.4	1030.6^{h} ±2.0	1047.5^{h} ±1.7	248.2^{abc} ±1.1	10.4^{g} ±0.3	9.8^{j} ±0.5	4.0^{g} ±0.1	6.8^{g} ±0.5	1026.1^{g} ±41.2	1036.9^{g} ±41.7	197.7^{ab} ±5.2	26.4^{d} ±0.9	11.8^{h} ±0.1
	2016_2	14.8^{de} ±0.3	42.2^{abc} ±4.2	1375.7^{efg} ±24.3	1432.7^{defg} ±19.8	193.8^{cde} ±8.9	27.1^{d} ±0.4	17.2^{f} ±0.4	14.8^{cd} ±0.8	38.2^{e} ±2.3	1324.3^{ef} ±50.0	1377.3^{f} ±46.9	203.9^{ab} ±9.7	26.7^{d} ±0.7	16.5^{f} ±0.7
‘IAC572’	**2015_1**	18.4^{a} ±1.5	43.9^{abc} ±1.1	1532.4^{cde} ±73.0	1594.7^{cd} ±72.6	240.3^{abcd} ±1.8	17.1^{e} ±0.1	11.8^{ghi} ±0.0	16.5^{bc} ±0.8	56.7^{bcd} ±8.9	1801.8^{bc} ±39.2	1875.0^{bcd} ±48.9	237.4^{ab} ±1.8	16.3^{f} ±0.1	11.8^{h} ±0.0
	2015_2	14.9^{cde} ±0.6	44.7^{abc} ±9.2	1551.4^{bcd} ±35.1	1611.0^{bc} ±43.8	268.9^{a} ±1.9	34.2^{b} ±0.6	23.8^{c} ±0.2	13.8^{de} ±0.2	39.2^{e} ±1.8	1874.8^{b} ±50.0	1927.9^{bc} ±52.1	221.1^{ab} ±3.9	31.8^{a} ±0.8	24.2^{b} ±0.3
	2016_1	4.0^{g} ±0.0	6.5^{d} ±0.5	698.6^{i} ±4.1	709.1^{i} ±3.5	238.0^{abcd} ±9.3	11.0^{g} ±0.4	10.1^{j} ±0.1	5.2^{g} ±0.4	12.2^{g} ±1.1	1460.4^{e} ±26.4	1477.7^{f} ±25.7	209.6^{ab} ±4.4	16.6^{ef} ±0.0	12.8^{g} ±0.0
	2016_2	17.4^{abc} ±0.1	33.4^{c} ±4.8	1294.1^{g} ±64.2	1344.9^{g} ±59.2	183.0^{de} ±3.9	28.1^{d} ±0.1	19.3^{e} ±0.1	19.3^{a} ±0.8	46.3^{de} ±3.0	1304.1^{f} ±13.5	1369.7^{f} ±9.7	213.7^{ab} ±1.8	29.5^{c} ±0.8	18.1^{e} ±0.1
‘SO4’	**2015_1**	18.0^{ab} ±0.4	50.9^{ab} ±3.7	1502.7^{cdef} ±91.9	1571.5^{cde} ±0.9	240.3^{abcd} ±0.9	16.1^{e} ±0.1	11.9^{gh} ±0.1	17.6^{ab} ±0.3	85.7^{a} ±2.8	1818.2^{bc} ±17.6	1921.3^{bc} ±14.4	246.9^{ab} ±0.4	17.6^{ef} ±0.1	12.8^{g} ±0.0
	2015_2	17.5^{ab} ±0.5	49.3^{ab} ±3.5	1804.1^{a} ±60.8	1871.4^{a} ±1.3	264.5^{ab} ±1.3	34.0^{b} ±0.8	25.7^{a} ±0.1	14.3^{cd} ±0.4	61.2^{bc} ±4.5	2043.2^{a} ±21.6	2118.7^{a} ±26.5	237.3^{ab} ±7.8	32.8^{a} ±1.2	25.7^{a} ±0.2
	2016_1	4.6^{fg} ±0.6	9.9^{d} ±0.7	1383.3^{defg} ±20.9	1397.9^{fg} ±1.1	231.8^{abcde} ±1.1	13.8^{f} ±0.4	9.7^{j} ±0.2	11.3^{f} ±1.1	25.6^{f} ±1.6	2064.9^{a} ±54.1	2101.7^{a} ±53.6	210.6^{ab} ±2.1	25.2^{d} ±0.2	16.5^{f} ±0.0
	2016_2	15.8^{bcde} ±1.1	53.8^{a} ±3.0	1563.1^{bc} ±46.6	1632.7^{bc} ±9.6	216.7^{abcde} ±9.6	30.7^{c} ±0.0	19.0^{e} ±0.1	15.4^{bcd} ±0.9	65.7^{b} ±1.8	1786.5^{bc} ±21.6	1867.6^{bcd} ±24.3	216.0^{ab} ±7.6	33.0^{a} ±1.2	21.6^{d} ±0.5
Rootstock *per* harvest	***Sig.***	***	***	***	***	ns	***	***	***	***	***	***	ns	***	***
Harvest date	***Sig.***	***	***	***	***	***	***	***	***	***	***	***	**	***	***
Rootstock *vs* harvest	***Sig.***	***	**	***	***	ns	***	***	***	***	***	***	ns	***	***
Rootstock *per* semester	***Sig.***	ns	ns	*	*	ns	*	ns	ns	*	***	***	ns	**	*
Semester	***Sig.***	**	**	*	*	ns	***	***	ns	ns	ns	ns	ns	***	***
Rootstock *vs* semester	***Sig.***	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Cultivar	***Sig***	**Monomeric**	ns	**Oligomeric**	***	**Polymeric**	***	**Total tannins**	***	**Tanning power**	ns	**ABTS**	**	**DPPH**	***

Means within the same column followed by different letters are significantly different according to the Tukey test ($p< 0.05$); ns: not significant; * significant differences at 95% confidence level; ** significant differences at 99.9% confidence level; *** significant differences at 99.99% confidence level; Harvest: 2015_1 (1st semester of 2015); 2015_2 (2nd semester of 2015); 2016_1 (1st semester of 2016); 2016_2 (2nd semester of 2016).

clone blends across four consecutive vintages. The data are presented by rootstock and harvest, including three tannin fractions (monomeric, oligomeric, and polymeric) and two antioxidant capacity assays (ABTS and DPPH). Significant effects were observed for condensed tannins, tanning power, and antioxidant capacity across clone origin, rootstock, harvest season, cultivar, and their interactions. Oligomeric and polymeric are derived from the condensation of flavan-3-ol monomers (proanthocyanidins), which play a central role in wine structure and ageing (Oliveira *et* al, 2020; Tzachristas *et al*., 2020).

The analysis of condensed tannins revealed significant variations and clear differences among clones, rootstocks, and vintages. The 'SO4' rootstock consistently showed the highest average levels of all tannin fractions and total condensed tannins in wines from both Portuguese and Spanish clones. The 2015_2 harvest exhibited the greatest concentrations, reaching 1871 mg/L in Portuguese clones and 2119 mg/L in Spanish clones grafted onto 'SO4'. These high values were accompanied by high tanning power, particularly in Portuguese clones grafted onto 'IAC572', which displayed the lowest tannin content (709 mg/L). This decline is consistent with the lower anthocyanin and phenolic levels reported earlier, and reflects the negative impact of shortened cycles and rainfall stress on phenolic ripening. These results highlight the combined influence of phenolic maturity, genotype (clone and rootstock), and climatic conditions on tannin accumulation and distribution. The predominance of the polymeric fraction suggests that wines from favorable harvests possess a more structured phenolic profile with enhanced ageing potential and oxidative stability. Conversely, the reduced tannin levels in 2016_1 wines may compromise mouthfeel, persistence, and capacity for long-term maturation. The strong performance of 'SO4' corroborates earlier studies in the São Francisco Valley, in which higher total tannin concentrations were reported in second-semester harvests, although the distribution among tannin fractions varied depending on vintage and cultivar (Oliveira *et al*., 2018; 2019a; 2019b).

Interestingly, wines from Portuguese clones exhibited maximum tanning power during the second-semester of 2015, whereas wines from Spanish clones reached their highest tanning power in the 2015_1 harvest, driven by high monomeric and polymeric tannin fractions. Antioxidant capacity was clearly higher for second semester harvests compared to first semester harvests (Table IV), which is consistent with observations in 'Touriga Nacional' wines by Oliveira *et al*. (2018). This variation highlights the complex interplay between cultivar, rootstock, and vintage, emphasising the need for tailored vineyard and winemaking practices to optimise phenolic extraction and wine stability in tropical semi-arid environments.

Tanning power, expressed in NTU/mL, reflects the astringent potential of wines through the turbidity induced by protein precipitation, which is affected by the concentration and composition of phenolic compounds. Differences in the proportions of monoglucosylated anthocyanins may therefore contribute to variations in visual appearance. According to He *et al*. (2010), the color expressed by anthocyanins depends on their structure: cyanidin (orange-red), peonidin (red), delphinidin (bluish-red), and pelargonidin (orange), petunidin and malvidin (bluish red).

The anthocyanin profile of tropical wines from Portuguese and Spanish *Vitis vinifera* clones grafted onto four rootstocks across four consecutive vintages provides valuable insights into the combined influence of genotype, rootstock, and climate on wine color attributes (De Rosas *et al*., 2022). In both wine types, harvest season significantly affected the concentration of all identified anthocyanins. The effect was most evident in wines from Portuguese clones, in which the rootstock influenced anthocyanins levels both within individual harvests and across vintages. In contrast, wines from Spanish clones showed no significant differences in petunidin-3-*O*-coumaroylglucoside and malvidin-3-*O*-coumaroylglucoside concentrations as a function of rootstock or harvest.

Semester effects were more variable, but generally significant for non-acylated anthocyanins, except for cyanidin-3-*O*-glucoside in wines from Spanish clones (Table V). The 2016_1 vintage consistently showed the lowest concentrations across clones and rootstocks, likely due to unfavourable ripening conditions. Conversely, the 2016_2 vintage presented the highest levels, underscoring the decisive role of seasonal climate in anthocyanins biosynthesis and accumulation. The presence of coumaroylated anthocyanins indicates potential for intramolecular copigmentation, which enhances color intensity and stability—an especially valuable trait in tropical wines where high temperatures and oxidative stress can accelerate color degradation (Enaru *et al*., 2021). The variability in anthocyanin profiles across vintages, clone origins, and rootstocks highlights the need for tailored viticultural and winemaking strategies in tropical regions. Clones with higher genetic capacity for anthocyanin synthesis, such as the Spanish clone, combined with rootstocks like 'IAC313', can improve phenolic quality. Moreover, a better understanding of seasonal impacts on anthocyanin accumulation can guide vineyard and harvest timing to optimise color atributes (Gordillo *et al*., 2018; Enaru *et al*., 2021.; De Rosas *et al*., 2022; Cheng *et al*., 2023; Chen *et al*., 2024a).

In conclusion, the anthocyanin composition, and consequently the color quality, of tropical wines results from a complex interaction between genetic factors, rootstock, and environmental conditions. These findings provide a foundation for targeted strategies to enhance visual appeal and stability in tropical wines. However, the multifaceted nature of terroir complicates the isolation of individual factors, as grape composition arises from a dynamic interplay between natural influences and human interventions (Blancquaert *et al*., 2019).

Sensory profile of the wines

The sensory evaluation of wines from Portuguese and Spanish clones grafted onto different rootstocks and harvested across vintages and semesters highlighted complex interactions among genetic, environmental, and management factors (Table VI). Overall, significant differences were mainly associated with vintage and semester, while rootstock effects were more dependent on their interaction with these temporal variables. Importantly, the considerable magnitude of some standard deviations observed in the data points to marked variability in panelist responses, reflecting the inherent subjectivity of sensory perception in wines. Furthermore, principal component analysis (PCA) did not reveal any major differences among the sensory data, indicating that neither rootstock nor harvest semester had a strong influence on the overall sensory profile under the studied conditions.

For wines from Portuguese clones, differences in hue were evident across vintages and semesters, with higher values in second-semester harvests, especially in 2015_2. This suggests that tropical second-semester conditions promoted the accumulation of phenolic compounds with greater color expression potential, in accordance with the findings of Oliveira *et al.* (2020). Among the rootstocks, 'IAC572' was associated with more intense color in 2015_2, standing out positively when compared with its performance in 2016_1. Conversely, 'SO4' often showed lower intensity values, with reduced stability and higher variability between replicates, suggesting weaker capacity for pigment accumulation or extraction.

Color intensity was generally higher in first-semester harvests, likely favored by milder conditions that reduce pigment degradation, while variability (as shown by wider standard deviations) was more evident in second-semester wines. This reinforces the role of seasonal climate in modulating color expression.

Table V

Monomeric anthocyanins (mg/L) in wines from Portuguese and Spanish clones of grapes produced in tropical semi-arid region in Brazilian northeastern, from four consecutive harvests

Rootstock (R)	**‘P1103’**				**‘IAC313’**				**‘IAC572’**				**‘SO4’**				**ANOVA (p-values)**					
Harvest (H)	**2015_1**	**2015_2**	**2016_1**	**2016_2**	**2015_1**	**2015_2**	**2016_1**	**2016_2**	**2015_1**	**2015_2**	**2016_1**	**2016_2**	**2015_1**	**2015_2**	**2016_1**	**2016_2**	**R/H**	**H**	**R×H**	**R/S**	**S**	**R×S**
Wines from Portuguese Clones																						
Del-3-glu	2.7^{ef}	2.9^{def}	1.3^{g}	3.8^{cde}	3.6^{cde}	4.4^{bc}	0.4^{g}	6.0^{a}	3.1^{cde}	3.3^{cde}	0.5^{g}	4.4^{bcd}	3.2^{cde}	1.5^{fg}	1.0^{g}	5.3^{ab}	***	***	***	ns	***	ns
Cyn-3-glu	0.4^{cd}	0.4^{cd}	0.4^{cd}	0.4^{cd}	0.6^{bcd}	0.5^{cd}	0.3^{cd}	0.9^{b}	0.6^{bcd}	0.3^{cd}	0.5^{cd}	0.5^{cd}	0.3^{cd}	1.8^{a}	0.2^{d}	0.7^{bc}	***	***	***	*	***	***
Peo-3-glu	1.5^{bcd}	1.1^{cde}	0.4^{de}	1.8^{bc}	1.5^{bcd}	3.2^{a}	0.3^{e}	1.9^{bc}	2.6^{ab}	1.2^{cde}	0.3^{e}	1.7^{bc}	1.3^{cde}	1.1^{cde}	0.2^{e}	1.8^{bc}	**	***	***	ns	**	ns
Pet-3-glu	1.7^{f}	1.9^{ef}	0.6^{g}	3.0^{bc}	2.6^{cd}	2.5^{cde}	0.3^{g}	4.0^{a}	0.2^{g}	2.0^{def}	0.4^{g}	3.4^{ab}	2.0^{def}	0.2^{g}	0.2^{g}	3.5^{ab}	***	***	***	ns	***	ns
Mal-3-glu	9.3^{ef}	7.6^{f}	3.8^{g}	18.8^{b}	13.1^{cd}	13.1^{cd}	1.9^{g}	22.7^{a}	14.3^{c}	9.1^{ef}	3.0^{g}	20.6^{ab}	11.5^{de}	7.0^{f}	2.7^{g}	21.0^{ab}	***	***	***	ns	***	ns
Del-3-ace	0.5^{defg}	0.4^{efgh}	1.0^{bc}	0.7^{cd}	0.4^{efgh}	1.8^{a}	0.6^{de}	0.5^{def}	0.6^{de}	0.2^{h}	0.2g^{h}	0.6^{de}	1.1^{b}	0.3^{fgh}	1.7^{a}	0.7^{cd}	***	***	***	**	ns	***
Cyn-3-ace	0.3^{gh}	0.3^{fgh}	1.0^{b}	0.5^{ef}	0.2^{hi}	0.3^{gh}	0.1^{i}	1.2^{a}	0.5^{efg}	0.3^{gh}	0.2^{hi}	0.8^{cd}	0.1^{i}	0.2^{hi}	0.9^{bc}	0.6^{de}	***	***	***	ns	ns	**
Peo-3-ace	0.3^{c}	nd	nd	nd	0.1^{d}	0.4^{a}	nd	nd	0.3^{bc}	0.4^{a}	nd	0.4^{a}	0.3^{bc}	0.1^{de}	nd	0.4^{a}	***	***	***	*	*	*
Pet-3-ace	0.7^{b}	nd	nd	nd	0.2^{f}	0.3^{cd}	nd	0.2^{f}	0.5^{c}	0.3^{de}	nd	0.2^{ef}	nd	1.0^{a}	nd	0.3^{def}	***	***	***	ns	ns	***
Mal-3-ace	0.5^{cd}	2.3^{a}	0.3^{d}	0.8^{bcd}	0.7^{bcd}	0.3^{d}	1.2^{bc}	0.7^{bcd}	0.8^{bcd}	2.3^{a}	1.3^{b}	0.7^{bcd}	0.7^{bcd}	1.3^{b}	0.4^{cd}	0.1^{d}	***	***	***	ns	***	**
Del-3-cou	0.7^{efg}	3.1^{a}	0.5^{fg}	0.6^{def}	0.5^{fg}	0.6^{efg}	1.4^{c}	0.8^{de}	0.3^{g}	1.4^{c}	1.1^{cd}	0.9^{de}	0.4^{g}	2.1^{b}	0.8^{def}	1.6^{c}	***	***	***	ns	ns	*
Peo-3-cou	0.8^{cde}	0.2^{f}	0.2^{f}	1.0^{bc}	0.9^{bcd}	0.6^{e}	0.1^{f}	1.2^{b}	0.7^{de}	0.8^{cde}	0.2^{f}	0.9^{cd}	2.1^{a}	0.6^{de}	0.3^{f}	0.9^{bc}	***	***	***	ns	ns	ns
Pet-3-cou	0.5^{bcd}	0.4^{cde}	0.1^{e}	0.2^{de}	0.5^{cd}	0.4^{cde}	0.1^{e}	0.7^{de}	0.5^{bcd}	0.2^{de}	0.2^{de}	0.8^{ab}	0.3^{de}	0.9^{a}	0.2^{de}	0.3^{de}	*	***	***	ns	**	ns
Mal-3-cou	2.1^{b}	1.5^{c}	0.3^{fg}	1.3^{cd}	2.1^{b}	1.3^{cd}	0.2^{fg}	1.0^{cd}	2.8^{a}	1.4^{cd}	0.2^{fg}	1.3^{cd}	1.3^{cd}	1.4^{cd}	0.7^{efg}	0.7^{ef}	***	***	***	ns	ns	ns
Total	22.0^{fg}	22.0^{fg}	9.9^{g}	32.9^{c}	26.9^{def}	29.8^{cd}	8.0^{g}	41.2^{a}	27.6^{de}	23.3^{ef}	8.2^{h}	37.0^{b}	24.7^{def}	19.6^{f}	9.2^{g}	39.9^{b}	***	***	***	ns	ns	ns
Wines from Spanish clones																						
Del-3-glu	2.3^{g}	3.8^{cde}	0.6^{h}	4.3^{bc}	3.0^{f}	4.1^{cd}	0.5^{h}	5.4^{a}	3.2^{ef}	5.0^{ab}	1.1^{h}	4.3^{bcd}	3.6^{def}	4.4^{bc}	0.9^{h}	4.3^{h}	***	***	***	ns	***	ns
Cyn-3-glu	0.7^{ab}	0.4^{bcd}	0.3^{cd}	0.5^{abcd}	0.5^{ab}	0.4^{bcd}	0.3^{d}	0.5^{abcd}	0.8^{a}	0.8^{a}	0.8^{a}	0.5^{bcd}	0.6^{ab}	0.6^{abc}	0.3^{cd}	0.3^{cd}	***	***	***	***	ns	ns
Peo-3-glu	1.5^{abc}	1.1^{c}	0.1^{e}	1.7^{ab}	1.5^{abc}	1.8^{a}	0.1^{e}	1.5^{abc}	1.9^{a}	1.3^{bc}	0.2^{e}	1.5^{abc}	1.6^{abc}	0.8^{d}	0.2^{d}	1.5^{abc}	***	***	***	*	***	*
Pet-3-glu	1.7^{e}	2.3^{de}	0.4^{f}	3.4^{ab}	2.6^{cd}	2.3^{de}	0.2^{f}	4.1^{a}	2.1^{de}	2.2^{de}	0.7^{f}	3.3^{bc}	2.0^{de}	1.7^{e}	0.7^{f}	3.2^{bc}	**	***	***	ns	***	ns
Mal-3-glu	7.5^{de}	10.2^{e}	2.9^{gh}	21.5^{ab}	9.2^{de}	10.7^{de}	1.3^{h}	24.6^{a}	11.6^{cd}	14.1^{c}	4.9^{fg}	21.0^{b}	10.5^{de}	8.0^{de}	3.7^{gh}	21.3^{b}	***	***	***	ns	***	ns
Del-3-ace	0.2^{e}	3.3^{a}	1.7^{bcd}	1.0^{cde}	0.7^{de}	1.6^{bcd}	0.5^{e}	0.7^{de}	1.1^{cde}	2.6^{ab}	0.2^{e}	0.9^{cde}	1.7^{bc}	2.8^{a}	0.2^{e}	0.7^{de}	***	***	***	ns	**	ns
Cyn-3-ace	0.7^{cd}	0.3^{def}	0.2^{def}	0.4^{def}	1.0^{bc}	1.8^{a}	0.6^{cdef}	0.1^{f}	0.7^{cde}	0.7^{cd}	0.5^{cdef}	0.2^{ef}	1.2^{b}	0.4^{def}	0.3^{def}	0.3^{def}	***	***	***	*	ns	ns
Peo-3-ace	0.4^{b}	0.1^{c}	nd	nd	nd	0.7^{a}	nd	0.3^{b}	0.3^{b}	0.1^{b}	nd	nd	nd	nd	nd	nd	***	***	***	***	ns	***
Pet-3-ace	0.1^{cd}	0.1^{d}	nd	nd	nd	0.1^{bc}	nd	0.2^{ab}	0.2^{a}	0.1^{bc}	nd	nd	nd	nd	nd	nd	***	***	***	**	ns	***
Mal-3-ace	0.9^{bcde}	0.6^{e}	1.0^{cde}	0.7^{bcde}	0.8^{cde}	1.2^{ab}	1.2^{a}	0.9^{bcde}	0.9^{abcde}	1.0^{abcd}	0.8^{cde}	0.7^{de}	0.8^{cde}	0.7^{cde}	0.7^{de}	0.7^{cde}	***	***	***	***	ns	ns
Del-3-cou	0.7^{def}	0.5^{def}	0.3^{efg}	0.7^{def}	1.3^{bc}	0.3^{efg}	nd	0.6^{def}	0.6^{def}	1.8^{ab}	0.9^{cde}	0.6^{def}	0.6^{def}	1.6^{ab}	1.9^{a}	1.1^{cd}	***	***	***	**	ns	ns
Peo-3-cou	0.1^{g}	0.8^{cd}	0.1^{g}	1.2^{ab}	0.6^{ef}	0.9^{cd}	0.2^{g}	1.3^{a}	0.7^{def}	0.8^{bc}	0.2^{g}	1.0^{bc}	0.7^{def}	0.5^{f}	0.3^{g}	1.1^{ab}	***	***	***	ns	***	*
Pet-3-cou	0.2^{f}	1.2^{a}	0.7^{bcd}	0.4^{def}	0.3^{ef}	0.9^{abc}	0.4^{def}	0.6^{cde}	0.8^{abc}	0.3^{def}	0.4^{def}	0.6^{cde}	0.3^{ef}	0.2^{f}	0.5^{cdef}	1.1^{ab}	ns	***	***	ns	*	ns
Mal-3-cou	2.1^{a}	1.3^{cd}	0.3^{ef}	1.2^{cd}	2.1^{a}	1.1^{d}	0.2^{f}	1.1^{d}	1.9^{ab}	1.4^{bcd}	0.3^{ef}	1.3^{cd}	1.7^{abc}	0.9^{de}	0.4^{ef}	1.2^{cd}	ns	***	ns	ns	ns	ns
Total	18.9^{f}	25.9^{de}	8.6^{gh}	36.8^{b}	23.5^{e}	28.0^{d}	5.5^{h}	41.7^{a}	26.7^{de}	33.2^{h}	11.1^{g}	35.8^{bc}	25.4^{de}	22.8^{ef}	9.9^{g}	36.9^{b}	ns	***	ns	ns	ns	ns

Means within the same row followed by different letters are significantly different according to the Tukey test ($p < 0.05$); ns: not significant); * significant differences at 95% confidence level; ** significant differences at 99.9% confidence level; *** significant differences at 99.99% confidence level; R/H: Rootstock *per* harvest; H: Harvest date; RxH: Rootstock *vs* harvest; R/S: Rootstock *per* semester; S: Semester; RxS: Rootstock *vs* semester. Harvest: 2015_1 (1st semester of 2015); 2015_2 (2nd semester of 2015); 2016_1 (1st semester of 2016); 2016_2 (2nd semester of 2016). *Non-acylated*: Del-3-glu (Delphinidin 3-*O*-glucoside); Cyn-3-glu (Cyanidin 3-*O*-glucoside); Peo-3-glu (Peonidin 3-*O*-glucoside); Pet-3-glu (Petunidin 3-*O*-glucoside); Mal-3-glu (Malvidin 3-*O*-glucoside); *Acetylated*: Del-3-ace (Delphinidin 3-*O*-acetylglucoside); Cyn-3-ace (Cyanidin 3-*O*-acetylglucoside); Peo-3-ace (Peonidin 3-*O*-acetylglucoside); Pet-3-ace (Petunidin 3-*O*-acetylglucoside); Mal-3-ace (Malvidin 3-*O*-acetylglucoside); *Coumaroylated*: Del-3-cou (Delphinidin 3-*O*-coumarylglucoside); Peo-3-cou (Peonidin 3-*O*-coumarylglucoside); Pet-3-cou (Petunidin 3-*O*-coumarylglucoside); Mal-3-cou (Malvidin 3-*O*-coumarylglucoside).

Table VI

Sensorial profile of Portuguese and Spanish clones' wines from grapes produced in tropical semi-arid region in Brazilian Northeast, from four consecutive harvests

Rootstock (R)	**'IAC313'**				**'IAC572'**				**'P1103'**				**'SO4'**				**ANOVA**					
Harvest (H)	**H1**	**H2**	**H3**	**H4**	**H1**	**H2**	**H3**	**H4**	**H1**	**H2**	**H3**	**H4**	**H1**	**H2**	**H3**	**H4**	**R/H**	**H**	**R×H**	**R/S**	**S**	**R×S**
Wines from Portuguese Clones																						
Visual Profile																						
Clarity	7.9 ±1.6	8.1 ±1.4	8.5 ±1.1	7.4 ±1.5	7.3 ±1.9	8.0 ±1.6	8.5 ±1.1	7.5 ±1.4	7.7 ±1.6	8.1 ±1.5	8.4 ±1.1	7.4 ±1.8	7.8 ±1.7	8.1 ±1.6	8.4 ±1.2	7.8 ±1.1	ns	*	ns	ns	ns	ns
Hue	7.7 ±1.0	8.2 ±1.2	3.5 ±1.1	6.6 ±0.8	7.7 ±1.0	8.1 ±1.3	5.1 ±1.4	7.2 ±1.1	7.3 ±1.4	8.6 ±0.7	2.9 ±1.1	7.0 ±0.6	8.0 ±0.8	8.3 ±1.1	4.8 ±1.8	7.5 ±0.8	*	***	*	ns	***	ns
Intensity	6.0 ±1.0	3.8 ±1.2	5.8 ±1.0	3.1 ±1.2	6.9 ±0.8	5.0 ±1.6	5.0 ±1.2	4.1 ±1.2	6.6 ±1.2	4.0 ±1.2	6.3 ±1.0	3.3 ±0.8	5.4 ±1.3	3.7 ±1.2	5.1 ±1.2	2.9 ±1.5	**	***	ns	**	***	*
Olfactive Profile																						
Intensity	5.1 ±1.4	5.9 ±1.0	5.1 ±1.2	5.1 ±1.6	5.6 ±1.4	5.9 ±1.5	4.9 ±1.0	5.3 ±1.4	6.0 ±1.3	6.4 ±0.5	5.5 ±0.9	5.6 ±0.6	5.0 ±2.0	5.8 ±1.1	4.3 ±1.4	5.3 ±1.4	ns	**	ns	ns	*	ns
Fruity	4.6 ±1.7	4.1 ±0.7	4.8 ±1.2	4.2 ±1.8	3.4 ±1.3	3.6 ±1.4	5.1 ±1.9	4.2 ±1.4	5.2 ±1.4	4.2 ±1.5	5.2 ±1.0	4.6 ±1.9	4.4 ±1.4	4.9 ±1.4	4.6 ±1.7	4.4 ±1.7	ns	ns	ns	ns	ns	ns
Floral	1.6 ±1.0	2.0 ±1.4	2.7 ±1.8	2.1 ±1.4	1.6 ±1.2	2.8 ±1.9	2.6 ±1.9	2.0 ±1.5	1.7 ±1.3	2.8 ±2.2	3.0 ±1.8	2.1 ±1.3	2.4 ±2.1	1.8 ±1.0	2.5 ±1.7	2.4 ±2.3	ns	ns	ns	ns	ns	ns
Spicy	2.8 ±2.0	2.1 ±1.2	2.8 ±2.3	2.5 ±2.0	2.5 ±2.0	3.0 ±2.0	2.7 ±2.6	2.8 ±2.0	4.1 ±2.4	2.9 ±1.4	2.8 ±1.8	2.8 ±2.1	2.8 ±2.0	3.2 ±2.1	2.3 ±2.0	2.7 ±2.4	ns	ns	ns	ns	ns	ns
Vegetable	2.2 ±2.0	2.8 ±1.6	4.2 ±2.2	3.1 ±1.8	3.2 ±2.9	2.7 ±1.8	3.5 ±2.1	3.7 ±1.8	1.8 ±1.8	2.3 ±2.0	3.1 ±2.0	3.5 ±2.0	2.8 ±1.9	2.3 ±1.7	2.9 ±2.3	3.4 ±2.1	ns	ns	ns	ns	ns	ns
Balance	5.2 ±0.7	4.0 ±1.3	4.7 ±1.0	4.8 ±1.1	2.7 ±1.5	3.9 ±1.6	4.8 ±1.8	4.6 ±1.1	5.1 ±1.5	4.3 ±0.9	4.4 ±1.4	4.9 ±0.6	3.8 ±1.1	4.9 ±1.2	5.0 ±1.4	4.6 ±1.1	ns	ns	**	ns	ns	ns
Taste Profile																						
Intensity	6.7 ±1.1	6.6 ±0.8	5.3 ±1.5	6.0 ±1.1	6.0 ±1.3	6.8 ±0.7	5.4 ±1.3	5.8 ±2.0	6.8 ±0.8	7.3 ±0.6	4.6 ±2.1	5.9 ±1.1	6.6 ±0.9	7.2 ±0.6	5.4 ±1.6	5.6 ±1.3	ns	***	ns	ns	*	ns
Body	6.1 ±1.1	6.0 ±1.1	2.9 ±1.2	5.5 ±1.0	5.9 ±1.9	6.2 ±1.2	3.8 ±1.9	5.3 ±1.4	6.3 ±1.2	6.5 ±1.5	2.5 ±1.0	5.5 ±1.0	6.4 ±1.2	6.6 ±1.0	3.2 ±1.7	5.2 ±1.1	ns	***	ns	ns	***	ns
Astringency	6.8 ±1.1	6.2 ±1.5	3.4 ±1.3	5.4 ±1.8	6.7 ±1.7	7.0 ±1.3	3.4 ±1.2	5.7 ±1.7	6.7 ±1.5	7.0 ±1.2	3.8 ±1.2	5.5 ±2.0	7.1 ±0.7	6.8 ±1.6	3.9 ±1.2	6.0 ±1.5	ns	***	ns	ns	**	ns
Acidity	4.3 ±1.6	4.3 ±1.6	6.7 ±1.2	5.0 ±2.4	3.7 ±1.5	4.0 ±1.6	6.7 ±1.2	5.1 ±1.7	4.0 ±1.6	4.1 ±1.6	6.9 ±1.5	4.9 ±2.3	4.1 ±1.4	4.1 ±1.7	7.2 ±1.4	4.9 ±1.6	ns	ns	***	***	ns	***
Sweetness	2.2 ±1.9	3.1 ±2.0	1.2 ±1.1	2.1 ±1.6	1.9 ±1.5	3.7 ±2.0	1.8 ±1.5	2.1 ±1.7	1.4 ±1.2	3.7 ±2.2	1.4 ±0.9	1.9 ±1.6	2.3 ±1.9	3.9 ±2.9	1.4 ±1.3	1.9 ±1.6	ns	***	ns	ns	***	ns
Bitterness	4.1 ±1.9	3.8 ±2.4	2.8 ±2.3	2.8 ±2.5	4.8 ±2.6	4.3 ±2.4	2.4 ±2.2	3.0 ±2.3	4.1 ±2.8	3.9 ±2.3	3.3 ±2.3	2.7 ±2.7	4.8 ±2.0	4.6 ±2.4	3.2 ±2.6	2.9 ±2.0	ns	**	ns	ns	ns	ns
Salty	2.1 ±1.4	2.6 ±2.0	3.3 ±2.9	2.6 ±2.2	2.0 ±1.5	2.4 ±1.8	3.6 ±2.7	3.2 ±2.4	3.3 ±2.3	2.5 ±1.9	3.2 ±2.3	2.5 ±2.2	2.0 ±1.7	2.5 ±2.0	3.4 ±2.7	2.7 ±2.4	ns	ns	ns	ns	ns	ns
Balance	4.9 ±0.6	4.9 ±0.8	3.6 ±1.6	4.7 ±0.9	3.2 ±0.5	4.0 ±1.3	3.9 ±1.7	4.5 ±1.6	4.5 ±0.8	4.8 ±0.9	3.3 ±1.2	5.1 ±1.4	4.3 ±0.7	4.5 ±1.0	3.2 ±1.6	4.5 ±1.3	ns	***	ns	ns	***	ns
Persistency	4.6 ±1.1	4.7 ±1.2	4.0 ±1.9	4.9 ±1.1	4.0 ±1.3	5.0 ±0.9	3.7 ±2.2	4.5 ±1.4	5.1 ±1.2	5.1 ±1.0	3.6 ±1.9	5.5 ±1.6	4.4 ±1.1	5.1 ±1.5	4.1 ±2.1	5.3 ±1.4	ns	**	ns	ns	***	ns
Final taste	4.7 ±0.8	5.3 ±0.8	3.6 ±1.1	5.0 ±0.7	3.5 ±1.0	5.0 ±1.1	3.7 ±1.9	4.6 ±1.8	5.3 ±1.0	5.2 ±1.2	3.9 ±1.2	5.3 ±1.2	4.2 ±0.6	5.1 ±1.2	3.5 ±1.6	5.1 ±1.2	ns	***	ns	ns	***	ns
Global app	5.2 ±0.9	4.9 ±1.0	3.5 ±1.5	5.3 ±0.5	2.7 ±1.0	4.2 ±1.8	4.3 ±2.0	4.7 ±1.4	4.9 ±1.1	5.2 ±1.4	3.3 ±1.1	5.5 ±0.9	5.0 ±0.5	4.9 ±1.2	3.5 ±1.6	5.0 ±1.1	*	***	**	ns	***	ns
Wines from Spanish Clones																						
Visual Profile																						
Clarity	7.7 ±1.8	8.0 ±1.7	8.2 ±1.3	7.8 ±1.2	7.6 ±1.9	8.0 ±1.7	8.1 ±1.4	7.4 ±1.8	8.1 ±1.7	8.1 ±1.6	8.4 ±1.2	7.7 ±1.4	7.5 ±2.1	7.9 ±1.7	8.4 ±1.3	7.4 ±1.8	ns	ns	ns	ns	ns	ns
Hue	8.1 ±0.9	8.1 ±1.1	5.6 ±1.0	6.2 ±1.1	7.9 ±1.4	8.3 ±1.1	5.5 ±1.1	7.7 ±0.8	8.5 ±0.9	8.1 ±1.1	5.3 ±1.1	7.0 ±0.8	8.4 ±1.1	8.7 ±1.1	5.3 ±0.9	8.0 ±1.8	ns	***	ns	ns	***	ns
Intensity	6.7 ±0.8	4.6 ±1.1	5.2 ±1.1	4.2 ±0.8	6.7 ±1.2	4.3 ±1.5	5.6 ±1.2	3.3 ±1.5	6.8 ±0.7	4.4 ±1.4	5.9 ±1.2	3.8 ±0.8	5.6 ±0.8	3.8 ±1.4	6.1 ±1.2	2.3 ±1.5	*	***	ns	*	***	ns
Olfactive Profile																						
Intensity	4.9 ±1.7	5.6 ±1.4	4.9 ±1.3	5.4 ±1.3	5.3 ±1.3	5.2 ±1.8	4.8 ±1.3	5.8 ±1.6	5.4 ±1.5	5.9 ±1.3	5.1 ±1.3	5.4 ±1.2	5.5 ±1.0	5.3 ±0.7	4.6 ±1.3	5.6 ±0.9	ns	ns	ns	ns	*	ns
Fruity	3.8 ±1.9	3.7 ±1.3	4.1 ±1.9	4.1 ±1.6	3.4 ±1.4	3.6 ±1.1	4.0 ±2.0	4.6 ±1.8	4.1 ±1.5	3.6 ±0.9	4.2 ±2.3	4.3 ±1.9	3.7 ±1.2	4.7 ±1.4	3.9 ±1.9	5.3 ±1.7	ns	ns	ns	ns	ns	ns
Floral	1.6 ±1.4	2.5 ±2.1	2.3 ±1.4	2.0 ±1.6	2.3 ±1.7	2.2 ±1.7	2.6 ±1.5	2.4 ±2.0	2.3 ±2.1	2.8 ±2.2	2.6 ±1.6	2.3 ±1.7	1.8 ±1.4	3.1 ±2.3	2.2 ±1.8	2.3 ±2.4	ns	ns	ns	ns	ns	ns
Spicy	3.3 ±2.3	2.8 ±1.7	2.8 ±2.2	2.4 ±2.1	3.4 ±2.7	2.4 ±1.8	2.2 ±2.2	2.9 ±2.2	4.0 ±2.9	3.2 ±2.2	2.8 ±2.4	2.5 ±2.2	2.6 ±2.2	3.3 ±1.9	2.6 ±2.6	3.2 ±2.0	ns	ns	ns	ns	ns	ns
Vegetable	2.1 ±2.0	2.6 ±1.8	2.8 ±2.0	3.4 ±1.8	2.1 ±1.8	2.6 ±1.3	2.9 ±1.8	3.2 ±1.9	2.4 ±2.0	3.8 ±2.4	3.5 ±2.5	2.8 ±2.0	2.4 ±1.9	2.3 ±1.7	3.1 ±2.5	2.8 ±1.8	ns	ns	ns	ns	ns	ns
Balance	4.4 ±1.8	4.1 ±1.9	4.3 ±1.1	4.6 ±1.0	4.7 ±1.0	4.7 ±1.1	4.3 ±1.3	4.6 ±1.5	4.3 ±1.6	4.3 ±1.0	4.5 ±1.4	4.8 ±1.1	5.0 ±0.8	5.1 ±1.0	3.8 ±1.6	5.6 ±1.1	ns	ns	ns	ns	ns	ns
Taste Profile																						
Intensity	6.6 ±1.3	6.4 ±0.8	5.7 ±1.3	5.7 ±1.1	6.5 ±1.3	6.5 ±1.1	5.4 ±1.2	6.4 ±1.3	6.3 ±1.2	6.3 ±0.9	5.5 ±1.5	6.3 ±1.1	6.2 ±1.0	6.9 ±1.2	5.3 ±1.6	6.4 ±1.0	ns	***	ns	ns	*	ns
Body	5.2 ±0.8	6.0 ±1.1	3.7 ±2.1	4.8 ±1.5	5.6 ±1.1	5.9 ±1.3	3.4 ±1.9	5.8 ±1.0	5.6 ±1.8	5.8 ±1.1	3.3 ±1.9	5.0 ±1.4	5.8 ±1.1	6.7 ±1.1	3.4 ±2.1	6.3 ±0.8	ns	***	ns	ns	***	ns
Astringency	5.9 ±2.1	6.8 ±1.2	4.5 ±1.9	5.4 ±1.9	6.8 ±1.3	6.3 ±2.2	3.9 ±1.5	6.7 ±1.5	6.7 ±1.7	6.2 ±1.9	4.8 ±1.8	6.3 ±2.1	6.8 ±0.6	7.3 ±1.3	4.3 ±1.6	6.4 ±1.7	ns	***	ns	ns	**	ns
Acidity	3.9 ±2.0	3.9 ±1.4	6.7 ±1.5	4.4 ±1.7	3.7 ±2.2	4.4 ±1.5	6.9 ±1.4	5.2 ±1.2	3.3 ±1.7	3.8 ±1.5	6.9 ±1.0	4.6 ±1.5	4.0 ±1.6	4.4 ±1.6	7.6 ±1.4	4.7 ±1.3	ns	***	ns	ns	**	ns
Sweetness	2.9 ±2.0	4.1 ±2.5	1.6 ±1.4	2.0 ±1.9	3.6 ±1.7	3.4 ±2.5	1.3 ±0.9	1.9 ±1.7	3.5 ±2.3	4.3 ±2.0	1.4 ±1.1	2.3 ±1.7	2.9 ±1.9	4.3 ±2.4	1.2 ±1.0	2.0 ±1.3	ns	***	ns	ns	*	ns
Bitterness	3.7 ±2.1	4.0 ±2.3	2.6 ±2.6	2.9 ±2.1	4.2 ±2.2	3.7 ±2.3	3.0 ±2.4	3.2 ±2.4	4.3 ±2.9	4.1 ±2.1	3.1 ±2.6	3.3 ±2.5	3.5 ±2.1	4.0 ±2.3	3.6 ±2.7	3.1 ±2.1	ns	ns	ns	ns	ns	ns
Salty	1.6 ±1.4	2.0 ±2.1	3.5 ±3.0	3.3 ±2.5	1.8 ±2.2	2.9 ±2.6	3.2 ±3.1	3.1 ±2.8	1.6 ±1.6	2.3 ±2.1	3.3 ±2.6	3.1 ±2.5	2.1 ±1.9	2.3 ±2.5	3.6 ±3.1	3.1 ±2.7	ns	*	ns	ns	ns	ns
Balance	4.4 ±0.6	4.3 ±1.0	3.6 ±1.8	4.2 ±1.2	3.9 ±0.6	4.9 ±1.0	3.3 ±1.3	4.5 ±0.9	3.2 ±0.7	4.4 ±0.9	3.5 ±1.5	4.3 ±1.7	4.1 ±0.7	4.7 ±1.5	2.9 ±1.4	5.2 ±1.5	ns	***	ns	ns	***	ns
Persistency	4.8 ±1.0	4.9 ±1.4	4.4 ±2.0	4.8 ±1.2	4.3 ±0.7	4.9 ±1.2	4.3 ±1.9	5.4 ±1.9	4.2 ±1.5	4.5 ±1.2	4.4 ±2.1	4.7 ±1.8	5.1 ±0.9	5.3 ±1.5	3.9 ±2.1	5.6 ±1.3	ns	ns	ns	ns	*	ns
Final taste	4.6 ±1.0	4.5 ±1.3	3.7 ±1.7	4.7 ±1.5	4.3 ±1.2	4.8 ±1.3	4.0 ±1.3	4.9 ±1.3	4.0 ±1.4	4.4 ±1.3	3.9 ±1.4	4.6 ±1.2	5.0 ±1.1	4.9 ±1.8	3.5 ±1.1	5.5 ±1.5	ns	**	ns	ns	**	ns
Global app	5.1 ±0.6	5.1 ±1.4	4.1 ±1.5	4.8 ±1.0	4.4 ±1.1	5.3 ±1.7	3.9 ±1.0	4.8 ±1.3	3.7 ±1.4	5.2 ±1.7	3.8 ±1.2	5.1 ±1.5	5.1 ±0.9	5.3 ±2.4	3.2 ±1.1	5.9 ±1.1	ns	***	ns	ns	***	ns

Means and standard deviations are presented for each variable. Correlations between factors were evaluated using the Tukey test ($p < 0.05$); ns: not significant; *significant differences at 95% confidence level; ** significant differences at 99.9% confidence level; *** significant differences at 99.99% confidence level; H1: 1st harvest of 2015 (1st semester); H2: 2nd harvest of 2015 (2nd semester); H3: 1st harvest of 2016 (1st semester); H4: 2nd harvest of 2016 (2nd semester). R/H: Rootstock *per* harvest; H: Harvest date; R×H: Rootstock *vs* harvest; R/S: Rootstock *per* semester; S: Semester; R×S: Rootstock *vs* Semester. Global app: Global appreciation.

The olfactory profile showed fewer consistent differences. Aroma intensity tended to be higher in second-semester harvests for both clone groups, pointing to greater grape maturity under longer ripening conditions. For Portuguese clones, wines grafted onto ‘P1103’ in 2015_1 showed improved olfactory balance, while those onto ‘IAC313’ presented greater variability in descriptors, such as fruity and floral, as reflected in higher standard deviations. This highlights how rootstock × season interactions can shape not only the mean scores but also the consistency of the sensory experience.

Taste attributes were the most affected dimension. In both clone groups, wines from second-semester harvests were generally described as having greater intensity, body, astringency, and gustatory balance. These results are consistent with longer ripening cycles, which tend to increase phenolic and ethanol contents, directly influencing perceptions of body, sweetness, and bitterness (Cretin *et al*., 2018). Still, high standard deviations in astringency and bitterness scores suggest that tasters’ perception of phenolic-derived attributes varied considerably, possibly reflecting differences in panelist sensitivity.

Acidity was more pronounced in first-semester harvests, particularly in 2016_1, which may be linked to earlier harvest under climatic constraints. This higher acidity negatively affected global appreciation, whereas second-semester wines—especially 2015_2 and 2016_2—had the highest overall acceptance, likely due to better balance and ripeness. The importance of acidity and ripeness for wine quality has also been underlined by Rogiers *et al.* (2022).

Regarding rootstocks, ‘IAC572’ tended to enhance taste balance and persistency, while ‘P1103’ was positively associated with global appreciation, especially in Portuguese clones. In contrast, ‘SO4’ was consistently linked to lower body and intensity scores, often with high variability, reinforcing its weaker performance in tropical conditions. These findings align with Oliveira *et al.* (2020) and Ausari *et al.* (2024), who emphasized the influence of rootstock on berry composition and wine sensory profile. Moreover, similarities with results obtained from vines grafted onto ‘110R’—genetically related to ‘P1103’—further reinforce the positive contribution of this rootstock to sensory quality.

In conclusion, the wines from the second-semester harvests generally achieved superior sensory quality, benefiting from longer ripening periods. Although rootstock effects were less consistent than seasonal effects, ‘P1103’ and ‘IAC572’ showed the most favorable contributions, while ‘SO4’ tended to limit color and taste attributes. The relatively high standard deviations observed for several descriptors indicate variability in panelist perception, underscoring the importance of considering both mean values and dispersion in interpreting sensory data.

Principal component analysis of wines (PCA)

Principal Component Analysis (PCA) provided valuable insights into the discrimination of tropical wines based on physicochemical composition and anthocyanin profiles, revealing that harvest season was the primary factor driving differentiation, whereas rootstock effects were minimal.

The PCA of physicochemical attributes explained 73.6% of the total variance (Figure 3A), with PC1 and PC2 accounting for 55.1% and 18.5%, respectively. Wine samples were mainly separated according to harvest date rather than rootstock. Wines from the 2015 vintages (first and second semesters) were grouped on the negative axis of PC1, influenced by alcohol content, total and polymeric tannins, total phenols, color intensity, flavonoids, and polymeric pigments—parameters linked to more structured, phenol-rich wines. Conversely, wines from 2016_1 and 2016_2 harvests were clustered on the positive axis, associated with higher total acidity, ionisation index, and anthocyanin copigmentation, particularly for 2016_2.

These patterns confirm that intra-annual climatic variation (e.g., rainfall, temperature) strongly affects ripening, phenolic maturity, and wine composition. Similar findings were reported by Gashu *et al*. (2020), Crook *et al*. (2021), Otto *et al*. (2023), and Fourment *et al*. (2024), who highlighted vintage-driven variability in tropical and subtropical vineyards. Oliveira *et al* (2018) also noted that grapes harvested in the first semester exhibited higher total acidity, reinforce the need to adapt winemaking protocols to the specific conditions of each vintage.

PCA of the HPLC-quantified monomeric anthocyanins (Figure 3C) explained only 41.5% of the total variability, showing weaker clustering than physicochemical variables. Nonetheless, the 2016_1 harvest stood out along PC1 (28.8%), consistent with its lower anthocyanin levels caused by adverse ripening conditions. PC2 (12.7%) indicated that delphinidin-3-*O*-glucoside-*p*-coumarate and malvidin-3-*O*-glucoside-*p*-acetate were discriminant for the 2015_2 harvest, suggesting enhanced anthocyanin acylation pathways. These derivatives are recognized for their superior color stability, which may favour wine longevity in tropical environments (Baris *et al*., 2024).

Despite the variability among vintages, PCA of individual harvests (Figure 3D) revealed no consistent rootstock-based separation, indicating that environmental effects outweighed rootstock in influence on anthocyanin profiles under irrigated studied. Overall, these results emphasise that in tropical viticulture, harvest timing and vintage conditions decisively shape wine composition, especially phenolic and pigment traits.

The richer tannin and pigment profiles observed in 2015 suggest that dry, cooler second-semester conditions enhance phenolic accumulation, while early-season harvests (like 2016_1) may yield wines of lower complexity unless compensated by specific viticultural or winemaking adjustments. The limited discriminatory role of rootstock under irrigation highlights the importance of focusing future research on phenology, water status, and microclimate management, in alignment with recent recommendations by Alonso-Forn *et al*. (2025) and Callili *et al*. (2022).

The PCA thus confirms that, under the semi-arid tropical conditions of northeastern Brazil, harvest season exerts the strongest effect on wine composition—particularly on phenolic compounds while rootstock effects remain secondary. These findings reinforce the need for vintage-specific vineyard and winery strategies in to optimise quality, stability, and sensory complexity of tropical wines.

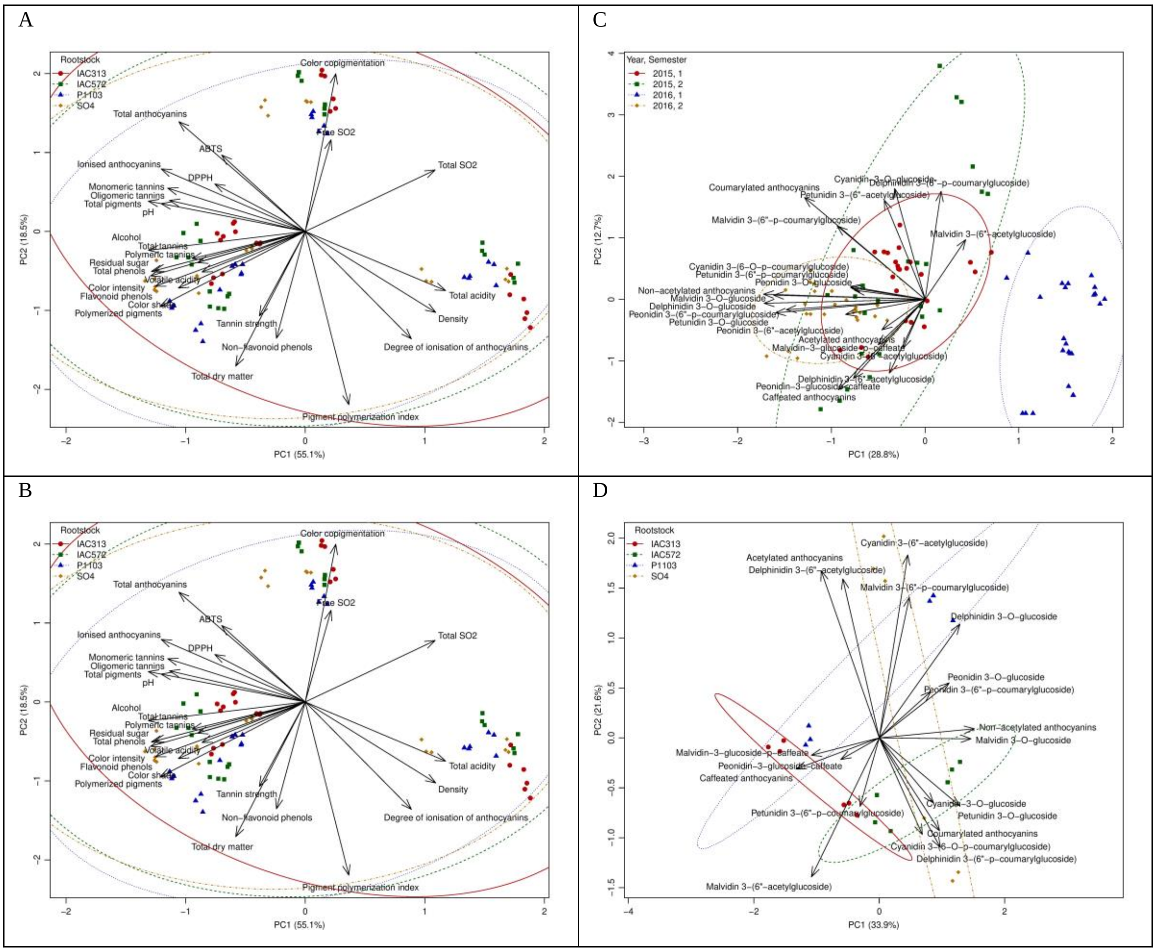

Figure 3. Principal component analyses (PCA) from physicochemical analysis of red wines from Portuguese and Spanish clones of according to the four consecutive harvest dates (seasons) (A) and four rootstocks (B) and evaluated of monomeric anthocyanins according to the four consecutive harvest dates (seasons) (C) and individual seasons, in 2016_1 (D).

CONCLUSIONS

This study demonstrated that, under tropical semi-arid conditions, harvest season exerts the strongest influence on the phenolic composition, antioxidant capacity, and color attributes of wines, with 2016_1 emerging as the least favourable vintage. Rootstock effects were more limited under irrigated conditions, although SO4 consistently contributed to higher phenolic and antioxidant values, particularly when combined with the Spanish clone.

Yield was also influenced by the interaction between rootstock and clone origin. The tropical rootstock ‘IAC313’ maintained higher production levels across harvests, while ‘SO4’ exhibited the lowest yields in specific semesters, particularly with Spanish clones. These findings reinforce that, in addition to their effects on wine composition, rootstock and clone combinations play a decisive role in vine productivity under tropical semi-arid conditions, and therefore should be carefully considered in vineyard planning and management.

The predominance of polymeric tannins, together with high tanning power in several experimental treatments, indicates that tropical wines can achieve a structured tannic profile with ageing potential and sensory complexity. The strong correlation between tannins, anthocyanins, and antioxidant capacity further highlights the dual role of phenolic compounds in shaping both wine quality and bioactive potential.

The significant interactions between rootstock, clone, and harvest timing highlight the complexity of vineyard and winemaking management in tropical regions. Therefore, adaptive practices such as strategic harvest scheduling, informed rootstock selection, and customised winemaking protocols aligned with local microclimatic conditions are essential to ensure the consistency and quality of tropical wines throughout the year.

Overall, the findings provide a foundation for refining viticultural and oenological practices in tropical regions, contributing to improved quality, stability, and distinctiveness of wines produced under these unique conditions. Future research should deepen the understanding of climate–genotype–rootstock interactions, particularly under changing climatic scenarios, to support the sustainable development of tropical viticulture.

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