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Research Article

Effects of Rootstock and Harvest Season on the Maturation of Portuguese and Spanish Clones of the Aragonez (syn. Tempranillo) Cultivar (*Vitis vinifera* L.) Grown Under Tropical Semi-Arid Conditions in Northeastern Brazil

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ABSTRACT

This study addresses the need to optimise clone and rootstock selection for high-quality wine production under tropical semi-arid conditions. It evaluated the effects of rootstock and harvest season on the maturation of Portuguese and Spanish clones of the Aragonez (syn. Tempranillo) grapevine cultivar (*Vitis vinifera* L.) grown under tropical semi-arid conditions in the São Francisco Valley, Brazil. Ten Tempranillo clones grafted onto four rootstocks were assessed over four consecutive harvests (two per year). Yield remained stable across all clone-rootstock combinations, regardless of the season. However, significant differences were observed in physicochemical traits, organic acid profiles, phenolic composition and colour parameters. Spanish clones, particularly E24 and E51, consistently exhibited higher levels of anthocyanins, total phenolics and condensed tannins in their wines, indicating greater likelihood for deeply coloured and bodied wines. Among the Portuguese clones, 60EAN and 110JBP stood out for their favourable acidity and anthocyanin profiles. Rootstock effects varied with season, with SO4 and IAC572 enhancing phenolic maturity, especially in second-semester harvests under warmer and drier conditions. Principal component analyses confirmed strong interactions among clone, rootstock and harvest timing, highlighting the complexity of genotype × environment × management relationships in tropical viticulture. These findings support the strategic use of diverse clone-rootstock combinations and flexible harvest scheduling to optimise grape quality and expand wine style possibilities in emerging warm-climate regions.

Keywords: Aragonez, chemical composition, grapevine clones, harvest season, rootstock affinity, São Francisco Valley, Tempranillo, viticulture

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INTRODUCTION

The quality of grapes grown in tropical and subtropical regions, such as Brazil, Venezuela, India and Thailand, has gained international recognition (Pereira, 2020). In Brazil, viticulture is concentrated in the South, Southeast and Northeast regions, with the main producing states being Rio Grande do Sul, Pernambuco, São Paulo, Paraná, Bahia, Santa Catarina and Minas Gerais. Pereira (2020) also states that the country is unique in presenting three distinct types of viticulture, determined by climatic conditions and vine management practices, as presented in Fig. 1. The three types are traditional viticulture (in temperate and subtropical climates, with one annual harvest), tropical semi-arid viticulture (with two harvests per year, possible at any time of the year), and winter viticulture (with pruning for production in autumn and harvesting in winter).

The São Francisco Valley (09°23'S, 40°30'W), located in the Northeast of Brazil, is characterised by a semi-arid tropical climate. Under such conditions, the combination of irrigation management and pruning practices enables grapevines to produce two to three crops per year. Irrigation scheduling is typically based on crop evapotranspiration (ETc), ensuring continuous growth and allowing the suppression of natural dormancy under tropical semi-arid conditions

This unique viticultural system has facilitated the growth of fine wine production with a distinct typicity, markedly different from wines produced in regions with more traditional viticultural management (Pereira *et al*., 2020).

Grafting of *Vitis vinifera* L., initially used to control phylloxera (*Daktulosphaira vitifoliae*), has expanded to include a wide range of North American rootstocks (Ollat *et al*., 2016). Beyond protecting against soil-borne diseases, grafting allows for the selection of genotypes adapted to diverse soils and climates. Modern rootstocks enhance tolerance to abiotic stresses, influence vine growth, phenology, yield and fruit quality, and support the diversification of viticultural strategies (Koundouras *et al*., 2008; Ibacache *et al*., 2016; Jin *et al*., 2016; Bascuñán-Godoy *et al*., 2017; Silva *et al*., 2017; Provost *et al*., 2021). Their use may also affect grape production under specific soil and climate conditions, particularly in emerging wine regions (Provost *et al*., 2021; Blank *et al*., 2022; Tecchio *et al*., 2022; Heller-Fuenzalida *et al*., 2023; Chen *et al*., 2024).

Grapevine clones affect grape quality significantly by modulating the physical-chemical composition of berries, including volatiles, phenolics, organic acids and sugars, particularly under variable climatic conditions (Arrizabalaga, 2018). Phenolic content

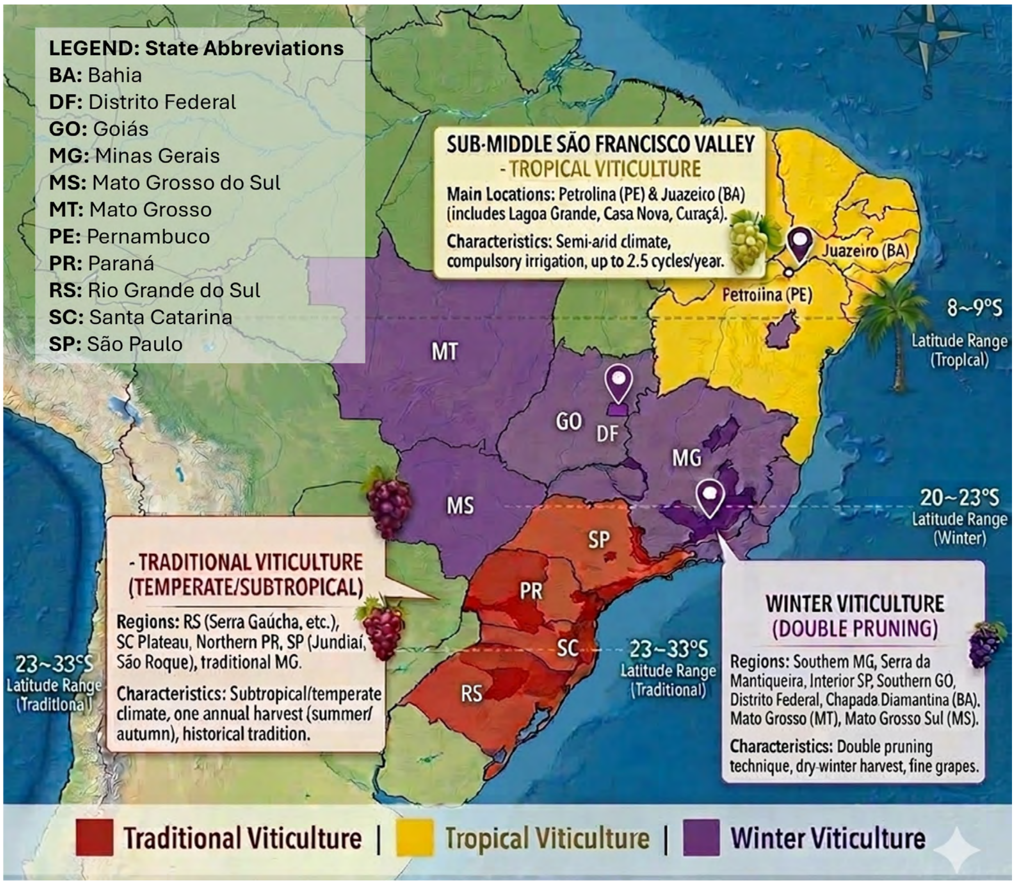

FIGURE 1 Climatic-based classification of Brazilian viticulture: traditional, tropical and winter production systems.

depends on genetic factors (variety and clone), environmental conditions (light, temperature, soil), and viticultural practices (canopy, irrigation, nitrogen and berry covering) (Peirano-Bolelli *et al.*, 2022; Ren *et al.*, 2023). Clonal diversity enables vineyards to utilise either mixed or single clones, influencing wine typicity and enhancing complexity through blending. The intravarietal diversity of *Vitis vinifera*, as in Tempranillo, supports the selection of heat-adapted genotypes without compromising quality, with clonal variation playing a key role in berry composition (Arrizabalaga-Arriazu *et al.*, 2020; Zombardo *et al.*, 2022). Carvalho *et al.* (2020) reported that Aragonez (syn. Tempranillo) displays notable clonal variability under abiotic stress, although clonal responses may vary across seasons. This highlights the complexity of genotype × environment interactions and the limitations of single-year evaluations in assessing field performance. Mucalo *et al.* (2020) suggest that harvest indicators should be locally adjusted, as grape composition patterns may vary according to site-specific environmental conditions.

The cultivar Aragonez (syn. Tempranillo) is also recognised for its substantial intravarietal variability in yield and composition (Gonçalves *et al.*, 2007; Gonçalves & Martins, 2019; Carvalho *et al.*, 2020). The present study examines this variability in the São Francisco Valley, a tropical semi-arid region in northeastern Brazil, where grape production relies heavily on controlled irrigation due to the region's low annual rainfall. According to Pagliarani *et al*. (2019), in addition to cultivation practices, the specific molecular responses of a grapevine clone can shape its agronomic traits under different environmental conditions. In this context, De Oliveira *et al.* (2019a) reported that the Syrah variety exhibits a distinct phenolic composition, characterised by high concentrations of anthocyanins and flavonoids, which provides potential for wines with high antioxidant capacity. Furthermore, De Oliveira *et al.* (2020) observed that Alicante Bouschet, cultivated in the region, exhibits phenotypic and chemical characteristics that make it a promising variety for high-quality wine production. Similarly, De Oliveira *et al.* (2018) showed that harvest season significantly affects the phenolic and oenological quality of 'Touriga Nacional' in Pernambuco due to intra-annual climate variability. In addition, the authors pointed out that Touriga Nacional, originally from Portugal, adapts well to the climatic conditions of the São Francisco Valley, presenting a phenolic profile favourable for wines with ageing potential. Therefore, genotype × environment interactions should be considered when designing viticultural strategies to improve grape quality. By evaluating distinct clones grafted onto different rootstocks and harvested across two years and contrasting seasons, the present study provides insights into how clones, rootstock and harvest season interact to modulate grape composition under tropical semi-arid conditions.

Taking above-mentioned into consideration, the objective of the study was to evaluate the effects of rootstock and harvest season (1st and 2nd semester) on the maturation and grape chemical composition of Portuguese and Spanish clones of the Aragonez (syn. Tempranillo) cultivar (*Vitis vinifera* L.) grown under tropical semi-arid conditions in northeastern Brazil.

MATERIALS AND METHODS

Description of vineyards, climatic conditions and harvest seasons

This study was conducted in an experimental vineyard established in 2006 at a partner winery in Pernambuco, Brazil (09°02′S, 40°11′W; 350 m above sea level), under a tropical semi-arid climate (Köppen: BSwh), on yellow eutrophic Argisol (soil taxonomy: Alfisol) (De Oliveira *et al.*, 2019b). Grapevines were trained on a single-wire trellis system, uniformly spur-pruned on a bilateral cordon, drip-irrigated (4 L/h, emitters spaced 1 m apart), spaced 1.0 × 3.0 m (3 333 vines/ha), and oriented North South.

Ten clones of *Vitis vinifera* L. cv. Aragonez (syn. Tempranillo) – five Portuguese (54EAN, 57EAN, 60EAN, 110JBP and BRSA) and five Spanish (E24, E51, 770, 776 and BRST) – were grafted onto four rootstocks: IAC313 (*V. riparia* × *V. rupestris* × *V. cinerea*), IAC572 [101-14 MGT (*V. riparia* × *V. rupestris*) × *V. caribaea*], SO4 (*V. berlandieri* × *V. riparia*) and P1103/Paulsen (*V. berlandieri* × *V. rupestris*). The BRSA and BRST clones, of unknown origin, were introduced to the region by the Brazilian Agricultural Research Corporation (EMBRAPA). A randomised complete block design was used with 10 marked vines per block (five blocks) for each clone × rootstock combination. Four harvests were assessed: March and September 2015, as well as February and August 2016. Harvest seasons were identified using a year_semester code (e.g., 2015_1, 2015_2), in which the first number indicates the year and the second the first or second semester, reflecting the biannual harvest cycle characteristic of this tropical semi-arid region. This notation is used consistently in the Results and Discussion. Harvest timing was established by the winery according to analytical measurements of soluble solids (°Brix), total titratable acidity, and the Brix-to-total acidity ratio, complemented by visual assessment of grape sanitary status and prevailing climatic conditions. Weather data (Fig. 2), including maximum, minimum and average air temperatures (°C) and rainfall (mm), were recorded via electronic sensors near the vineyard and compared to the local 30-year climate normal. Owing to the region's climate, two harvests occurred annually.

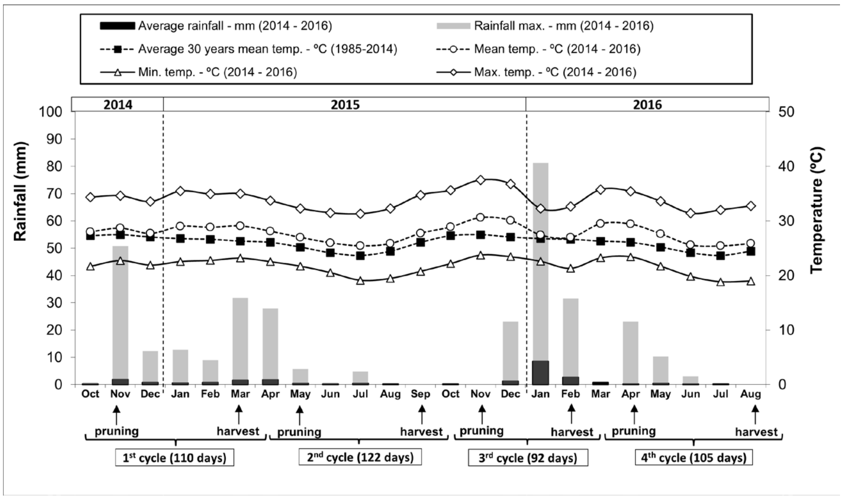

FIGURE 2 Meteorological data during the four harvest seasons in a tropical semi-arid climate of Brazil.

Yield components

Yield per plant was determined at harvest by weighing all grape clusters collected from each experimental unit and expressing this as kg per plant. Berry weight was calculated from the same sample of 200 berries collected per clone × rootstock combination, and the average mass was expressed in grams. These variables were subjected to the same factorial analysis of variance (clone × rootstock × harvest season) described for the physicochemical parameters.

Technological maturity parameters and grape phenolic compounds

In this study, technological maturity refers to the stage of grape ripening defined by parameters directly related to winemaking suitability. Grapes were sampled randomly for each clone × rootstock combination from different vines and bunch zones (base, middle, tip; inner and outer), with 200 berries collected for each clone × rootstock combination. The must obtained from pulp by berry pressing was used to assess technological parameters: pH, total soluble solids, total acidity, tartaric and malic acids, all of which were evaluated according to methodologies described by the International Organisation of Vine and Wines (OIV, 2014). All methods of analysis were performed in triplicate for each experimental sample.

The phenolic composition was analysed by macerating the skins and seeds remaining after must extraction for 24 hours at 20°C using a 96% ethanol solution and a tartaric acid solution (pH 3.2), as described by Carbonneau and Champagnol (1993). The extract was then centrifuged at 3 500 rpm for 10 to 15 minutes and used for spectrophotometric analyses of total phenols, non-flavonoids, flavonoids, total anthocyanins, colour intensity and hue, tannin power, and individual monomeric anthocyanins. According to Royo *et al.* (2021), under identical maceration conditions, extraction efficiency depends mainly on the grape tissue and, to a lesser extent, on maturity level. This may help explain the differences observed among harvest seasons in the present study.

Analyses were carried out using extracts prepared according to the method of Carbonneau and Champagnol (1993) to determine total phenols (Ribéreau-Gayon, 1970), non-flavonoid and flavonoid phenols (Kramling & Singleton, 1969), total anthocyanins (Ribéreau-Gayon & Stonestreet, 1965), as well as colour intensity and hue (OIV, 2014). Tannin power was also assessed using a turbidimetric method (De Freitas & Mateus, 2001). Three independent analytical determinations were performed for each clone–rootstock combination in each harvest season.

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

Flavanols were separated from the grape skin and seed extracts remaining after pressing using a Sep-Pak C18 cartridge (Waters, USA), with monomeric, oligomeric and polymeric fractions extracted using ethyl ether and methanol (for both oligomeric and polymeric) respectively, following Sun *et al*. (1998a). The flavanol content in each fraction was determined by the vanillin assay (Sun *et al*., 1998b) and quantified using standard curves from grape seed flavanol monomers, oligomers and polymers (Sun *et al.*, 1998a, 1998b, 2001). C18 cartridge extractions and vanillin assays were performed in triplicate.

Separation and quantification of individual monomeric anthocyanins by HPLC

Individual monomeric anthocyanins were identified and quantified using HPLC equipment (Perkin-Elmer, USA), equipped with a Series 200 pump and LC95 UV/Visible detector. Separation was achieved on a reverse-phase C18 column (250 mm x 4 mm, 5 µm particle size), protected by a matching pre-column, both supplied by LichroCart (Merck, Germany). Fourteen anthocyanin compounds were separated and analysed according to the method, and conditions were as described by Roggero *et al*. (1986), with quantification based on a standard curve prepared using malvidin 3-*O*-glucoside ($R^2 = 0.981$). All analyses on grape extracts were performed in triplicate.

Statistical analysis

All physicochemical analyses were performed in triplicate. Analysis of variance (ANOVA) and multivariate analysis (principal component analysis – PCA) were applied to all variables studied. Tukey's HSD test was employed for multiple mean comparisons among clones, rootstocks and harvest dates, as well as their interactions. Statistical significance was considered at the 95% confidence level. All analyses were carried out using the R software package (R Core Team, 2020).

RESULTS AND DISCUSSION

Yield components and basic technological parameters varied significantly among clones, rootstocks and harvest seasons (Table 1). Berry weight and yield showed consistent differences between Portuguese and Spanish clones across the four harvests evaluated.

Yield, chemical composition, and technological: clone, rootstock, and harvest season effects

The yield and berry weight of Portuguese and Spanish clones grafted onto five different rootstocks did not vary significantly, indicating stable productive performance under the tropical semi-arid conditions studied (Table 1).

These results suggest that the evaluated clones maintained consistent vigour and fruit development regardless of rootstock, in agreement with findings by De Oliveira *et al*. (2020) under similar climatic conditions. However, Fig. 3 shows that some clones exhibited higher yields in specific semesters, reflecting productive variability associated with seasonal factors. This finding supports the strategic use of more than one clone in vineyard planning to buffer seasonal effects, as suggested by Mucalo *et al.* (2020).

In contrast, significant differences were identified in several chemical and phenolic parameters. Portuguese clones exhibited lower total soluble solids (TSS) and higher total acidity than Spanish clones, indicating a fresher sensory profile in both the grapes and the corresponding wines. Clone 54EAN had the lowest TSS (20.0 °Brix), while E24 and E51 exceeded 22 °Brix, indicating more efficient sugar accumulation. These patterns align with the differences in thermal adaptation reported by Carvalho *et al.* (2020) and Han *et al.* (2023). While malic acid did not vary significantly, likely due to compensatory effects between synthesis and degradation, tartaric acid and pH differed between clones. Spanish clones showed higher pH and lower acidity, favouring a softer acid profile.

The interaction between rootstock and harvest date significantly influenced most chemical traits, particularly total soluble solids (TSS), pH, total acidity, and the composition of organic acids (Table 2). This reflects the dynamic nature of grapevine response under tropical conditions, where thermal amplitude and irrigation strategies may modulate metabolite accumulation differently across seasons. These findings reinforce the dynamic nature of grapevine responses under tropical and warm-climate conditions, where thermal amplitude and irrigation strategies may modulate metabolite accumulation throughout the season, as previously demonstrated (Yu *et al*., 2022; Oliver-Manera *et al*., 2023; Rodas *et al*., 2023; Maniero *et al*., 2025).

Among the Portuguese clones, TSS varied notably with harvest season, ranging from 17.1 °Brix to 27.8 °Brix. The highest values were observed during the second semester of 2015 (e.g., IAC572 and SO4), a period typically characterised by lower rainfall and greater radiation. Similar seasonal trends were seen in Spanish clones, although with slightly narrower TSS ranges. These results confirm the critical role of harvest timing in determining sugar accumulation under tropical conditions, as observed by De Oliveira *et al*. (2020) in Alicante Bouschet grown under similar climatic conditions in Brazil.

Total acidity also varied strongly across harvests and rootstocks, ranging from 3.8 g/L to 9.4 g/L in Portuguese clones. The first semester of 2016, generally associated with higher precipitation, yielded grapes with significantly higher total acidity and lower pH values. This seasonal effect may be linked to reduced respiratory degradation of organic acids under less intense heat and greater canopy vigour. Malic acid showed similar behaviour, with the highest concentrations recorded in the 2016_1 harvest season, regardless of rootstock. Notably, Spanish clones tended to retain slightly higher malic acid concentrations, suggesting either greater metabolic resilience or phenological delay. Tartaric acid, in contrast, was less influenced by season; however, significant differences among rootstocks were observed in the 2015_2 and 2016_2 harvest seasons, indicating a season-dependent rootstock effect.

Yield per vine varied significantly across harvest seasons and rootstocks, reflecting the strong influence of seasonal climatic conditions. Higher yields were generally observed under more favourable water

TABLE 1 **Yield, grape physicochemical and phenolic content of Portuguese and Spanish clones of Aragonez (syn. Tempranillo) in a tropical semi-arid region, Northeast Brazil.**

	Portuguese clones					Spanish clones					ANOVA
Parameter	54EAN	57EAN	60EAN	110JBP	BRSA	770	776	BRST	E24	E51	(p-values)
Yield (kg/vine)	1.78	1.62	1.84	1.49	1.77	1.61	1.61	1.69	1.57	1.91	ns
Berry weight (g)	1.26	1.19	1.24	1.21	1.26	1.26	1.23	1.29	1.19	1.25	ns
Classic analyses											
Total soluble solids (°Brix)	20.0^{b}	22.2^{a}	21.7^{a}	22.4^{a}	21.8^{a}	21.3^{a}	22.1^{a}	21.9^{a}	21.5^{a}	22.1^{a}	***
pH	3.80^{b}	3.86^{a}	3.87^{a}	3.87^{ab}	3.88^{a}	3.86^{ab}	3.90^{a}	3.83^{b}	3.87^{ab}	3.88^{a}	***
Total acidity (g/L)	6.7^{a}	6.0^{b}	6.0^{b}	6.2^{b}	6.1^{b}	5.7^{c}	5.6^{c}	5.6^{c}	5.5^{c}	5.7^{c}	***
Organic acids (g/kg)											
Malic acid	5.5	5.0	4.8	4.9	4.7	5.2	5.1	4.9	4.8	5.1	ns
Tartaric acid	3.5^{a}	3.5^{a}	3.5^{a}	3.6^{a}	3.3^{a}	3.5^{a}	3.5^{a}	3.1^{b}	3.5^{a}	3.6^{a}	***
Colour and global phenolic compounds											
Total phenols (mg/kg)	652.2^{b}	747.5^{ab}	772.3^{a}	780.3^{a}	661.7^{b}	714.7^{a}	780.0^{a}	802.3^{a}	759.6^{a}	746.9^{a}	***
Non-flavonoids (mg/kg)	43.9^{b}	65.1^{a}	61.3^{a}	63.3^{a}	50.4^{b}	55.5^{b}	63.4^{ab}	61.8^{ab}	61.0^{ab}	70.4^{a}	***
Flavonoids (mg/kg)	286.5	245.7	320.6	301.3	283.8	270.6	286.0	306.6	286.3	234.2	ns
Total anthocyanins (mg/kg)	321.7^{a}	436.6^{a}	390.3^{ab}	415.5^{a}	327.5^{b}	388.5^{a}	430.5^{a}	433.8^{a}	442.3^{a}	442.3^{a}	***
Colour intensity (a.u.)	7.082^{b}	9.095^{a}	9.241^{a}	9.246^{a}	7.042^{b}	7.808^{a}	8.916^{a}	9.197^{a}	8.178^{a}	8.143^{a}	***
Colour tonality (a.u.)	0.821^{a}	0.571^{b}	0.589^{ab}	0.579^{b}	0.615^{ab}	0.570^{a}	0.574^{a}	0.562^{a}	0.581^{a}	0.598^{a}	*
Condensed tannins (mg/g)											
Monomeric	0.94	0.87	1.03	1.18	1.12	1.41	1.63	1.60	1.60	1.49	ns
Oligomeric	2.50	2.38	2.34	2.67	2.55	3.20	3.51	3.66	3.26	2.94	ns
Polymeric	53.47^{ab}	57.54^{ab}	57.74^{ab}	59.90^{a}	49.18^{b}	63.45^{a}	59.06^{a}	67.26^{a}	66.03^{a}	64.77^{a}	***

TABLE 1 (CONTINUED)

Parameter	Portuguese clones					Spanish clones					ANOVA (p-values)
	54EAN	57EAN	60EAN	110JBP	BRSA	770	776	BRST	E24	E51	
Total tannins	56.93^{ab}	60.80^{ab}	61.12^{ab}	63.75^{a}	52.86^{b}	68.07^{a}	64.20^{a}	72.53^{a}	70.89^{a}	69.21^{a}	***
Tannin power (NTU/mL)	63.2	57.7	64.4	64.5	55.6	73.7	85.9	78.8	90.0	84.6	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. Total acidity is expressed as tartaric acid equivalent. Total phenols, flavonoids and non-flavonoids are expressed as gallic equivalents. Total anthocyanins are expressed as malvidin equivalents. a.u. (absorbance unit, measured at 520 nm). Concentration expressed in fresh weight of grape.

availability, whereas drier seasons resulted in moderate reductions. Among yield components, berry weight showed a more moderate response to rootstock. In Portuguese clones, IAC313 consistently promoted higher berry weights, particularly in the 2015_2 and 2016_2 harvest seasons. The variation was less pronounced in Spanish clones, although slight increases were observed under P1103 and IAC572 during drier conditions.

These differences in berry weight may have contributed to subsequent variations in juice composition, discussed below.

The statistical significance of the interactions (rootstock × harvest and rootstock × semester) across most parameters underscores the importance of matching rootstock performance with seasonal patterns in tropical regions. The absence of a consistent best-performing rootstock across all conditions indicates the necessity of strategic planning when defining harvest dates and clone-rootstock combinations for optimising grape composition. Taken together, these findings highlight the pronounced influence of seasonal variability on grape quality attributes under tropical conditions and reinforce the need for precision viticulture strategies, including flexible harvest scheduling and careful rootstock selection tailored to specific climate windows.

Global phenolic composition

Regarding phenolic composition, E24 and E51 stood out for total phenols, anthocyanins and non-flavonoids, while the Portuguese clone 60EAN also reached high anthocyanin levels, indicating potential for deeply coloured wines. Although flavonoid and early-stage tannin fractions (monomeric and oligomeric) did not differ significantly (Table 3), variations in polymeric and total condensed tannins were evident, with clones E24, E51 and 110JBP presenting the highest levels, which are crucial for wine structure and ageing potential. These findings are consistent with reports on the genetic regulation of anthocyanin biosynthesis (Suriano *et al.*, 2016; Arrizabalaga *et al.*, 2018, Arrizabalaga-Arriazu *et al.*, 2020; Dou *et al.*, 2024). Colour intensity was also higher in Spanish clones, especially E24 and E51, reinforcing their suitability for red wine production.

Clones E24, E51 and 110JBP presented the highest levels, which are crucial for wine structure and ageing potential. Colour intensity was also higher in Spanish clones, especially E24 and E51, reinforcing their suitability for red wine production. Overall, although yield was stable, marked compositional differences were observed among clones. Spanish clones, particularly E24 and E51, displayed superior phenolic and colour traits. Among Portuguese clones, 60EAN and 110JBP exhibited favourable profiles in terms of acidity and anthocyanins, supporting their potential

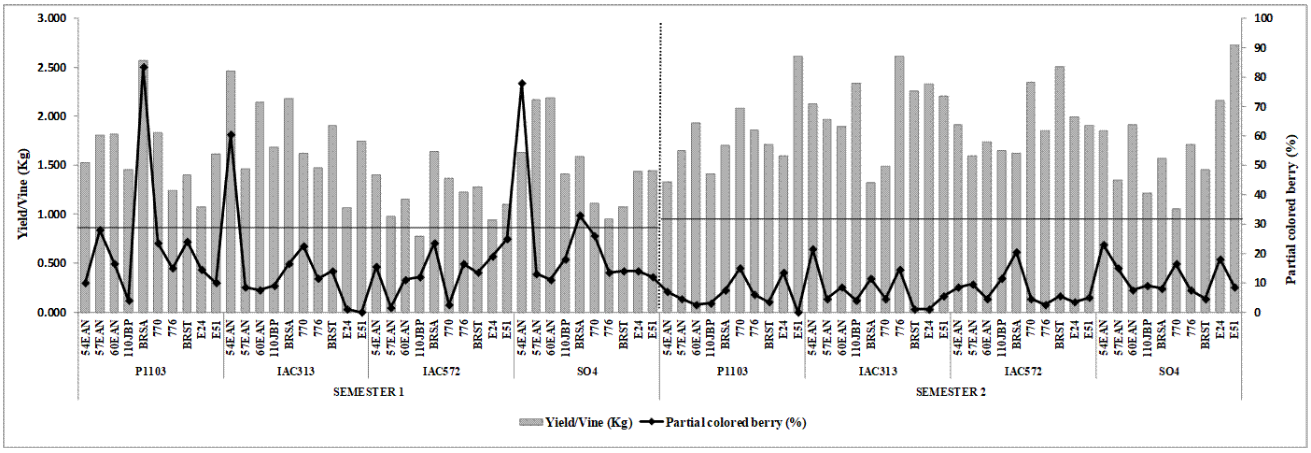

FIGURE 3 Yield and percentage of partially coloured berries of Portuguese and Spanish Aragonez (syn. Tempranillo) clones grafted onto different rootstocks across two harvests per year in tropical semi-arid Northeast Brazil.

for well-balanced wines.

Fig. 3 further reveals productive variability between semesters, reinforcing the feasibility of using multiple clones to mitigate seasonal effects. According to Carvalho *et al.* (2020), the significant genetic variability observed in traits such as acidity and phenolics, combined with generally low correlations across seasons, supports the strategic selection of well-adapted clones for tropical viticulture.

These results indicate a clear genotype × environment interaction, as the magnitude and direction of phenolic responses varied among clones depending on harvest season and rootstock. For instance, Spanish clones showed consistently higher anthocyanin and colour intensity levels, whereas differences in tannin fractions were more season-dependent (Table 3). Such variability reinforces the importance of site-specific clonal evaluation in tropical viticulture, as previously highlighted by Mucalo *et al.* (2020).

For both Portuguese and Spanish clones, the harvest season significantly affected the accumulation of total phenols, flavonoids, non-flavonoids and anthocyanins ($p < 0.0001$; ANOVA results presented in Table 3), confirming the strong influence of seasonal environmental conditions, such as thermal amplitude and radiation, on berry phenolic composition in tropical regions. These findings illustrate not only the genotype effect, but also the importance of the rootstock–scion interaction under varying seasonal conditions. The observed differences in phenolic accumulation among Portuguese and Spanish clones, depending on both rootstock and harvest date, highlight a complex genotype × environment × management interaction. In this context, the results align with Carvalho *et al.* (2020), who reported significant genetic variability for key quality traits and generally low genetic correlations between them across seasons. This suggests that clonal performance is highly dependent on environmental conditions, thereby reinforcing the potential for selecting specific clones that are better adapted to particular seasonal or climatic scenarios in tropical viticulture. These results are further supported by recent studies highlighting the dynamic nature of vine responses under tropical and warm-climate conditions, where temperature variability and irrigation management modulate metabolic outcomes across seasons (Yu *et al.*, 2022; Rodas *et al.*, 2023; Oliver-Manera *et al.*, 2023; Maniero *et al.*, 2025).

Among rootstocks, P1103 and IAC 572 were frequently associated with higher mean levels of total phenols and anthocyanins in specific harvest seasons, as shown in Table 3, particularly in 2015_2 and 2016_2, which are typically warmer and drier, although this effect was not consistent across all combinations. These results indicate that phenolic accumulation was influenced not only by genotype, but also by season-dependent rootstock–scion interactions.

The interaction between rootstock and harvest was statistically significant for most phenolic classes, highlighting that the influence of rootstock on secondary metabolism is modulated by environmental conditions. Similarly, the rootstock × semester interaction was particularly relevant for flavonoids and anthocyanins. These seasonal shifts were more pronounced in the Portuguese clones, whose phenolic profiles exhibited greater variability from harvest to harvest than those of the Spanish clones, suggesting distinct physiological responses to climatic stressors. Furthermore, the clonal origin group effect was significant for total phenols, non-flavonoids and anthocyanins ($p < 0.01$), reinforcing the contribution of the clonal genetic background to the phenolic composition. In general, Spanish clones accumulated more anthocyanins, while Portuguese clones tended to show higher total phenol content, depending on the rootstock.

TABLE 2 Berry weight and chemical composition of grapes from Portuguese and Spanish clones of Aragonez (syn. Tempranillo) by rootstock in a tropical semi-arid region, Northeast Brazil.

		Portuguese clones						Spanish clones					
			Chemical composition						Chemical composition				
Rootstock	Harvest	Berry weight (g)	TSS (°Brix)	pH	Total acidity (g/L)	Malic acid (g/kg)	Tartaric acid (g/kg)	Berry weight (g)	TSS (°Brix)	pH	Total acidity (g/L)	Malic acid (g/kg)	Tartaric acid (g/kg)
P1103	2015_1	1.180^{Bb}	$21.5^{Ab} \pm 1.7$	$4.10^{ABa} \pm 0.0$	$4.4^{Ad} \pm 0.0$	$4.2^{Ab} \pm 0.7$	$3.3^{Bb} \pm 0.3$	1.060^{Ac}	$24.2^{Ab} \pm 0.7$	$4.22^{Aa} \pm 0.1$	$4.1^{Ad} \pm 0.3$	$4.3^{Ab} \pm 1.0$	$3.6^{BCa} \pm 0.6$
	2015_2	1.294^{ABa}	$26.7^{ABa} \pm 1.0$	$3.95^{BCb} \pm 0.1$	$5.4^{Ac} \pm 0.1$	$4.3^{ABb} \pm 0.4$	$4.5^{ABa} \pm 0.3$	1.408^{Ba}	$25.7^{Aa} \pm 0.4$	$4.12^{Ab} \pm 0.0$	$4.4^{ABc} \pm 0.2$	$3.1^{Ac} \pm 0.3$	$3.9^{ABa} \pm 0.1$
	2016_1	1.058^{Bc}	$18.0^{Ac} \pm 1.0$	$3.61^{ABd} \pm 0.1$	$9.2^{ABa} \pm 0.1$	$5.5^{Ba} \pm 0.4$	$3.3^{Ab} \pm 0.1$	1.126^{Abc}	$17.3^{ABd} \pm 0.3$	$3.61^{Ad} \pm 0.1$	$8.5^{Ba} \pm 0.3$	$8.7^{ABa} \pm 0.5$	$2.6^{Ab} \pm 0.3$
	2016_2	1.136^{Bb}	$21.7^{Ab} \pm 1.0$	$3.81^{Ac} \pm 0.1$	$6.3^{Bb} \pm 0.0$	$5.8^{Ba} \pm 0.4$	$3.1^{ABb} \pm 0.7$	1.218^{Bb}	$20.7^{ABc} \pm 1.3$	$3.78^{Bc} \pm 0.1$	$5.5^{Bb} \pm 0.4$	$4.6^{Ab} \pm 0.5$	$3.0^{ABb} \pm 1.3$
IAC313	2015_1	1.374^{Aa}	$21.6^{Bb} \pm 1.4$	$4.10^{ABa} \pm 0.1$	$3.8^{Bd} \pm 0.1$	$3.6^{Ac} \pm 0.9$	$3.6^{Ab} \pm 0.3$	1.110^{Ac}	$23.8^{Ab} \pm 1.2$	$4.13^{Ba} \pm 0.1$	$3.9^{Ad} \pm 0.2$	$3.6^{BCc} \pm 0.4$	$4.2^{Aa} \pm 0.8$
	2015_2	1.366^{Aa}	$26.4^{Aa} \pm 1.3$	$3.92^{Cb} \pm 0.1$	$5.5^{Ac} \pm 0.0$	$3.7^{Bc} \pm 0.4$	$4.7^{Aa} \pm 0.5$	1.598^{Aa}	$25.8^{Aa} \pm 0.5$	$3.89^{Bb} \pm 0.0$	$4.7^{Ac} \pm 0.2$	$3.1^{Ac} \pm 1.2$	$4.4^{Aa} \pm 0.1$
	2016_1	1.162^{Ab}	$17.1^{Ad} \pm 1.8$	$3.56^{Bd} \pm 0.1$	$9.4^{Aa} \pm 0.0$	$8.1^{Aa} \pm 0.4$	$3.0^{Bc} \pm 0.2$	1.036^{Ac}	$18.2^{Ad} \pm 0.6$	$3.53^{Bd} \pm 0.1$	$8.5^{Ba} \pm 0.5$	$8.9^{ABa} \pm 4.4$	$2.7^{Ab} \pm 1.3$
	2016_2	1.404^{Aa}	$19.9^{Bc} \pm 1.7$	$3.73^{Bc} \pm 0.1$	$6.6^{ABb} \pm 0.0$	$5.6^{Bb} \pm 0.5$	$3.1^{ABc} \pm 0.1$	1.386^{Ab}	$20.7^{ABc} \pm 0.8$	$3.77^{Bc} \pm 0.1$	$5.4^{Bb} \pm 0.5$	$4.9^{Ab} \pm 0.4$	$2.9^{Bb} \pm 0.1$
IAC572	2015_1	1.150^{Bb}	$22.6^{Ab} \pm 1.3$	$4.16^{Aa} \pm 0.1$	$3.9^{ABd} \pm 0.1$	$3.5^{Ac} \pm 0.4$	$2.9^{Cb} \pm 0.4$	1.094^{Ac}	$23.5^{Ab} \pm 1.1$	$4.18^{ABa} \pm 0.0$	$4.1^{Ac} \pm 0.1$	$4.0^{ABc} \pm 0.7$	$3.4^{Cb} \pm 1.2$
	2015_2	1.304^{Aa}	$27.6^{Aa} \pm 1.1$	$4.08^{Ab} \pm 0.1$	$5.4^{Ac} \pm 0.2$	$4.8^{Ab} \pm 0.5$	$4.4^{Ba} \pm 0.2$	1.508^{ABa}	$25.2^{Aa} \pm 1.1$	$4.09^{Ab} \pm 0.0$	$4.1^{Cc} \pm 0.3$	$3.1^{Ad} \pm 0.5$	$4.1^{ABa} \pm 0.1$
	2016_1	1.208^{Ab}	$17.7^{Ad} \pm 1.5$	$3.64^{Ad} \pm 0.0$	$8.3^{Ca} \pm 0.0$	$5.2^{Bb} \pm 0.2$	$3.0^{Bb} \pm 0.1$	1.116^{Abc}	$17.8^{Ad} \pm 0.9$	$3.61^{Ad} \pm 0.1$	$8.5^{Ba} \pm 0.6$	$8.5^{Ba} \pm 0.6$	$2.9^{Ac} \pm 0.1$
	2016_2	1.362^{Aa}	$19.9^{Bc} \pm 0.7$	$3.73^{Bc} \pm 0.1$	$6.9^{Ab} \pm 0.0$	$6.6^{Aa} \pm 0.5$	$3.0^{Bb} \pm 0.2$	1.262^{ABc}	$21.5^{Ac} \pm 0.6$	$3.92^{Ac} \pm 0.1$	$5.3^{Bb} \pm 0.3$	$5.1^{Ab} \pm 0.5$	$3.1^{ABbc} \pm 0.1$
SO4	2015_1	1.202^{Ba}	$21.9^{Ab} \pm 1.1$	$4.05^{Ba} \pm 0.0$	$4.1^{ABd} \pm 0.1$	$3.8^{Ab} \pm 0.4$	$3.4^{ABb} \pm 0.4$	1.090^{Ab}	$22.5^{B} \pm 1.1$	$4.00^{Ca} \pm 0.1$	$4.1^{Ac} \pm 0.3$	$3.2^{Cc} \pm 0.7$	$4.0^{ABa} \pm 0.6$
	2015_2	1.220^{Ba}	$27.8^{Aa} \pm 0.3$	$3.99^{Ba} \pm 0.1$	$5.1^{Ac} \pm 0.0$	$3.8^{Bb} \pm 0.3$	$4.5^{ABa} \pm 0.2$	1.366^{Ba}	$24.9^{A} \pm 1.0$	$3.87^{Bb} \pm 0.1$	$4.4^{BCc} \pm 0.4$	$2.5^{Ad} \pm 0.4$	$3.7^{Bab} \pm 0.5$
	2016_1	1.160^{Aa}	$17.5^{Ad} \pm 1.4$	$3.61^{ABb} \pm 0.0$	$8.7^{BCa} \pm 0.0$	$5.3^{Ba} \pm 0.3$	$2.8^{Bc} \pm 0.2$	1.186^{Ab}	$16.6^{B} \pm 0.9$	$3.50^{Bd} \pm 0.0$	$9.4^{Aa} \pm 0.5$	$9.2^{Aa} \pm 0.5$	$2.8^{Ac} \pm 0.1$
	2016_2	1.166^{Ba}	$18.8^{Bc} \pm 0.9$	$3.63^{Cb} \pm 0.1$	$7.0^{Ab} \pm 0.1$	$6.0^{ABa} \pm 0.5$	$3.3^{Ab} \pm 0.2$	1.128^{Bb}	$20.5^{B} \pm 1.5$	$3.67^{Cc} \pm 0.1$	$6.5^{Ab} \pm 0.3$	$4.8^{Ab} \pm 0.8$	$3.4^{Ab} \pm 0.4$

TABLE 2 (CONTINUED)

		Portuguese clones						Spanish clones					
			Chemical composition						Chemical composition				
Rootstock	Harvest	Berry weight (g)	TSS (°Brix)	pH	Total acidity (g/L)	Malic acid (g/kg)	Tartaric acid (g/kg)	Berry weight (g)	TSS (°Brix)	pH	Total acidity (g/L)	Malic acid (g/kg)	Tartaric acid (g/kg)
Rootstock per harvest date	Sig.	***	**	***	ns	**	***	***	***	***	***	***	***
Harvest date	Sig.	***	***	***	***	***	***	***	***	***	***	***	***
Rootstock vs harvest date	Sig.	**	***	***	***	***	***	ns	**	***	***	***	***
Rootstock per semester	Sig.	***	ns	ns	ns	ns	ns	**	ns	***	ns	ns	*
Semester	Sig.	***	***	ns	ns	ns	***	***	***	ns	***	***	*
Rootstock vs semester	Sig.	ns	ns	ns	ns	***	ns	ns	ns	ns	ns	ns	ns
Clonal origin group	Sig.	ns	ns	**	***	ns	ns						

Means followed by different uppercase or lowercase letters within the same column indicate significant differences between rootstocks in the same harvest (uppercase) or across harvests for the same rootstock (lowercase), according to Tukey's 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 equivalent. TSS (total soluble solids). Concentrations expressed in g/kg fresh weight of grape.

TABLE 3 Phenolic compounds in grapes from Portuguese and Spanish clones of Aragonez (syn. Tempranillo) by rootstock in a tropical semi-arid region, Northeast Brazil.

		Global phenolic compounds							
		Portuguese clones				Spanish clones			
Rootstock	Harvest	Total phenols (mg/kg)	Flavonoids (mg/kg)	Non-flavonoids (mg/kg)	Total anthocyanins (mg/kg)	Total phenols (mg/kg)	Flavonoids (mg/kg)	Non-flavonoids (mg/kg)	Total anthocyanins (mg/kg)
P1103	2015_1	$798.95^{Ab} \pm 0.03$	$738.37^{Ab} \pm 0.05$	$60.58^{Bb} \pm 0.02$	$199.95^{Bb} \pm 0.08$	$1\,198.51^{Aa} \pm 0.01$	$1\,124.53^{Aa} \pm 0.05$	$73.97^{Ab} \pm 0.02$	$300.22^{Aa} \pm 0.08$
	2015_2	$977.00^{Ba} \pm 0.04$	$892.92^{Ba} \pm 0.04$	$84.09^{Ba} \pm 0.03$	$305.98^{Aa} \pm 0.05$	$746.90^{ABb} \pm 0.07$	$657.05^{Bbc} \pm 0.01$	$89.28^{Aa} \pm 0.02$	$237.54^{Ab} \pm 0.05$
	2016_1	$466.00^{Ac} \pm 0.03$	$439.95^{Ac} \pm 0.01$	$26.27^{Ac} \pm 0.00$	$96.43^{Ac} \pm 0.08$	$596.07^{Ac} \pm 0.04$	$570.81^{Ac} \pm 0.00$	$25.25^{Ac} \pm 0.01$	$123.19^{Ac} \pm 0.08$
	2016_2	$875.22^{Aab} \pm 0.03$	$814.29^{Aab} \pm 0.04$	$54.75^{Ab} \pm 0.00$	$284.96^{Aa} \pm 0.02$	$768.16^{Ab} \pm 0.03$	$696.47^{Ab} \pm 0.01$	$71.67^{Bb} \pm 0.01$	$242.35^{Bb} \pm 0.02$
IAC313	2015_1	$886.07^{Aa} \pm 0.03$	$826.06^{Aa} \pm 0.02$	$60.02^{Bb} \pm 0.01$	$243.92^{ABa} \pm 0.03$	$916.70^{Ca} \pm 0.03$	$846.96^{Ca} \pm 0.05$	$69.73^{Aa} \pm 0.02$	$253.56^{Ba} \pm 0.03$
	2015_2	$827.48^{Ca} \pm 0.02$	$732.94^{Ca} \pm 0.07$	$94.47^{ABa} \pm 0.02$	$244.93^{Ba} \pm 0.05$	$866.74^{Aa} \pm 0.00$	$791.79^{Aab} \pm 0.06$	$74.94^{Ba} \pm 0.03$	$241.53^{Aa} \pm 0.05$
	2016_1	$420.69^{Ac} \pm 0.01$	$393.92^{Ac} \pm 0.08$	$27.38^{Ac} \pm 0.00$	$76.57^{Ab} \pm 0.08$	$454.99^{Ab} \pm 0.06$	$575.12^{Ac} \pm 0.04$	$22.99^{Ab} \pm 0.00$	$133.38^{Ab} \pm 0.08$
	2016_2	$657.92^{Bb} \pm 0.02$	$604.14^{Bb} \pm 0.03$	$53.67^{Ab} \pm 0.02$	$193.06^{BCa} \pm 0.03$	$781.35^{Aa} \pm 0.01$	$708.22^{Ab} \pm 0.03$	$73.12^{Ba} \pm 0.01$	$261.57^{Ba} \pm 0.03$
IAC572	2015_1	$867.34^{Aa} \pm 0.03$	$789.66^{Aa} \pm 0.07$	$77.68^{Ab} \pm 0.01$	$254.93^{Ab} \pm 0.06$	$1\,060.53^{Ba} \pm 0.03$	$979.28^{Ba} \pm 0.03$	$81.24^{Aa} \pm 0.01$	$283.05^{ABa} \pm 0.06$
	2015_2	$978.90^{Ba} \pm 0.02$	$870.24^{Ba} \pm 0.00$	$108.52^{Aa} \pm 0.02$	$313.90^{Aa} \pm 0.08$	$623.22^{Bc} \pm 0.05$	$532.85^{Cc} \pm 0.00$	$90.36^{Aa} \pm 0.02$	$207.67^{Ab} \pm 0.08$
	2016_1	$482.82^{Ac} \pm 0.02$	$453.95^{Ac} \pm 0.06$	$27.90^{Ad} \pm 0.00$	$103.83^{Ad} \pm 0.02$	$613.82^{Ac} \pm 0.00$	$592.63^{Ac} \pm 0.08$	$21.19^{Ab} \pm 0.00$	$127.45^{Ac} \pm 0.02$
	2016_2	$641.73^{Bb} \pm 0.01$	$589.00^{Bb} \pm 0.03$	$53.13^{Ac} \pm 0.01$	$165.88^{Cc} \pm 0.09$	$880.60^{Ab} \pm 0.00$	$791.47^{Ab} \pm 0.05$	$89.11^{Aa} \pm 0.03$	$317.33^{Aa} \pm 0.09$
SO4	2015_1	$874.54^{Ab} \pm 0.03$	$816.44^{Ab} \pm 0.08$	$58.09^{Bb} \pm 0.00$	$253.44^{Ab} \pm 0.09$	$866.46^{Ca} \pm 0.04$	$792.46^{Ca} \pm 0.01$	$73.99^{Aa} \pm 0.02$	$256.11^{ABab} \pm 0.09$
	2015_2	$1\,100.14^{Aa} \pm 0.04$	$1\,001{,}52^{Aa} \pm 0.05$	$98.80^{Aa} \pm 0.05$	$356.56^{Aa} \pm 0.05$	$751.83^{Aa} \pm 0.04$	$680.14^{ABa} \pm 0.01$	$71.67^{Ba} \pm 0.02$	$212.12^{Ab} \pm 0.05$
	2016_1	$469.97^{Ac} \pm 0.00$	$438.50^{Ac} \pm 0.04$	$31.34^{Ac} \pm 0.00$	$102.87^{Ac} \pm 0.03$	$561.59^{Ab} \pm 0.05$	$530.68^{Ab} \pm 0.00$	$30.90^{Ab} \pm 0.00$	$121.82^{Ac} \pm 0.03$
	2016_2	$771.08^{Ab} \pm 0.01$	$728.86^{Ab} \pm 0.09$	$41.56^{Ac} \pm 0.02$	$222.20^{Bb} \pm 0.00$	$816.77^{Aa} \pm 0.00$	$746.09^{Aa} \pm 0.03$	$70.67^{Ba} \pm 0.00$	$271.41^{Ba} \pm 0.00$

TABLE 3 (CONTINUED)

		Global phenolic compounds							
		Portuguese clones				Spanish clones			
Rootstock	Harvest	Total phenols (mg/kg)	Flavonoids (mg/kg)	Non-flavonoids (mg/kg)	Total anthocyanins (mg/kg)	Total phenols (mg/kg)	Flavonoids (mg/kg)	Non-flavonoids (mg/kg)	Total anthocyanins (mg/kg)
Rootstock per harvest	Sig.	***	***	***	ns	**	***	**	***
Harvest date	Sig.	***	***	***	***	***	***	***	***
Rootstock vs harvest	Sig.	***	***	**	***	***	***	***	***
Rootstock per semester	Sig.	**	***	ns	ns	ns	***	ns	***
Semester	Sig.	***	ns	***	***	ns	***	***	***
Rootstock vs semester	Sig.	*	**	ns	*	ns	***	ns	ns
Clonal origin group	Sig.	**	ns	***	***				

Means followed by different uppercase or lowercase letters within the same column indicate significant differences between rootstocks in the same harvest (uppercase) or across harvests for the same rootstock (lowercase), according to Tukey's 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 phenols, flavonoids and non-flavonoids expressed as gallic equivalents. Total anthocyanins expressed as of malvidin equivalents. Concentrations expressed in g/kg fresh weight of grape.

Taken together, these results underscore the importance of selecting appropriate rootstock–scion combinations tailored to the specific climatic conditions of each harvest season, as previously reported by Clingeleffer *et al.* (2019), Zombardo *et al.* (2020), Clingeleffer *et al.* (2022), Santesteban *et al.* (2023) and Marcuzzo *et al.* (2025). This notion is further supported by meta-analytical data showing that certain rootstocks can decouple sugar and pH responses in grapes, offering adaptive flexibility under future climate scenarios (e.g., Yu *et al.*, 2022; Rodas *et al.*, 2023). In addition, long-term field trials with Chardonnay, Cabernet Sauvignon and Shiraz under hot climate conditions revealed significant rootstock × scion interactions affecting fruit composition, reinforcing the need for combination-specific management (Clingeleffer *et al.*, 2019). Such combinations may enable viticulturists in tropical semiarid regions to optimise grape phenolic maturity according to the desired wine profile.

Grape colour parameters

Grape must colour intensity was significantly affected by rootstock ($p < 0.01$), harvest date ($p < 0.0001$) and their interaction ($p < 0.0001$) in both clonal origin groups (Table 4), indicating that colour expression was strongly influenced by seasonal factors and rootstock–scion combinations, as previously reported by Clingeleffer *et al.* (2019, 2022), who demonstrated significant rootstock effects on fruit colour under warm climate conditions (Table 4).

In general, the second semesters (particularly 2015_2 and 2016_2) were associated with higher colour intensities, especially in grapes from Portuguese clones grafted onto SO4 and IAC 572 (Table 4). Conversely, grapes harvested in the first semesters (e.g., 2016_1) consistently exhibited the lowest colour intensity values across all rootstocks, likely due to lower anthocyanin accumulation under shorter ripening periods or less favourable climatic conditions, in agreement with Rodas *et al.* (2023) and Maniero *et al.* (2025), who demonstrated that environmental stress and thermal amplitude during ripening strongly modulate anthocyanin biosynthesis in tropical climates. Tonality values remained relatively stable and were not significantly influenced by rootstock or clonal origin group, although minor seasonal effects were observed for the Spanish clones, suggesting a more stable colour hue – possibly related to genotypic buffering capacity, as previously discussed by Carvalho *et al.* (2020). Taken together, these results indicate that the expression of grape colour in tropical conditions is highly dependent on harvest timing and rootstock effects, reinforcing the need for targeted rootstock–scion selection under tropical viticulture scenarios (Zombardo *et al.*, 2020; Yu *et al.*, 2022).

Condensed tannins and tanning power in grape berries

As shown in Table 5, condensed tannin fractions and tanning power exhibited significant variation across clones, rootstocks, and harvest seasons.

Both Portuguese and Spanish clones displayed clear differences in the accumulation of monomeric, oligomeric and polymeric tannins, reflecting strong genotype × environment × rootstock interactions, as previously highlighted by Clingeleffer *et al.* (2019, 2022), De Oliveira *et al.* (2018, 2019a, 2019c, 2020) and Zombardo *et al.* (2020), who emphasise the importance of matching rootstock–scion combinations to site-specific conditions.

The influence of harvest season was particularly evident, with significantly higher total tannin values generally observed during the second semester of 2016 (2016_2), especially in grapes grafted onto SO4 and IAC572 (Table 5). These results align with Rodas *et al.* (2023) and Maniero *et al.* (2025), who reported that increased thermal amplitude and radiation during late season ripening favour the accumulation of skin phenolics under tropical conditions. Similarly, Yu *et al.* (2022) demonstrated that delayed harvest under high-radiation environments can enhance phenolic extractability and influence the balance between different tannin fractions.

Among the Portuguese clones, grapes from SO4 in 2016_2 reached the highest total condensed tannin content (93.03 mg/g), while in Spanish clones, the highest value was recorded with the same rootstock and harvest (98.74 mg/g) (Table 5). This seasonal trend was consistent with higher tanning power values in the same combinations, suggesting increased phenolic development and extractability under warmer and drier late-season conditions. Conversely, lower tannin levels and tanning power were observed in grapes harvested during the wetter first semesters (e.g., 2015_1 and 2016_1), possibly due to dilution effects and lower skin phenolic development, as suggested by Oliver-Manera *et al.* (2023) for grapes under humid and cloudy conditions.

Statistical analyses revealed highly significant effects for rootstock, harvest, and their interaction ($p < 0.0001$) across nearly all tannin variables, including total and polymeric fractions. In addition, cultivar effects were also significant, with Spanish clones generally accumulating more total tannins, particularly in the polymeric form, which may influence wine structure and astringency potential. The modulation of tannin accumulation by rootstock and harvest date under tropical conditions is consistent with the clonal variability and genotype × environment interactions reported by Carvalho *et al.* (2020).

TABLE 4 Berry colour in Portuguese and Spanish clones of Aragonez (syn. Tempranillo) by rootstock in a tropical semi-arid region, Northeast Brazil.

		Portuguese clones		Spanish clones	
Rootstock	Harvest	Colour intensity (a.u. x 10)	Colour tonality (a.u.)	Colour intensity (a.u. x 10)	Colour tonality (a.u.)
P1103	2015_1	8.21^{Ab} ± 0.1	0.68^{Aa} ± 0.00	12.04^{Aa} ± 0.1	0.68^{Aa} ± 0.01
	2015_2	12.04^{BCa} ± 1.4	0.62^{ABb} ± 0.02	9.87^{Ab} ± 0.6	0.62^{ABb} ± 0.03
	2016_1	3.57^{Ac} ± 1.5	0.54^{Ac} ± 0.02	4.26^{Ac} ± 0.4	0.54^{Ac} ± 0.00
	2016_2	10.57^{Aa} ± 0.1	0.52^{Ac} ± 0.01	8.45^{Ab} ± 0.2	0.52^{Ac} ± 0.03
IAC313	2015_1	9.06^{Aab} ± 0.0	0.64^{Ba} ± 0.00	10.21^{Ba} ± 0.1	0.63^{Ba} ± 0.01
	2015_2	10.43^{Ca} ± 1.2	0.63^{Aa} ± 0.00	9.86^{Aa} ± 0.1	0.63^{Aa} ± 0.02
	2016_1	3.36^{Ac} ± 0.3	0.52^{ABb} ± 0.05	4.52^{Ab} ± 0.9	0.52^{ABb} ± 0.01
	2016_2	7.61^{Bb} ± 0.4	0.49^{Bb} ± 0.04	8.85^{Aa} ± 0.7	0.49^{Bb} ± 0.01
IAC572	2015_1	9.72^{Ab} ± 0.1	0.66^{ABa} ± 0.00	11.31^{ABa} ± 0.1	0.66^{ABa} ± 0.00
	2015_2	12.04^{ABa} ± 0.6	0.60^{Bb} ± 0.02	7.97^{Bb} ± 0.8	0.60^{Bb} ± 0.03
	2016_1	3.56^{Ad} ± 0.4	0.53^{Ac} ± 0.01	4.41^{Ac} ± 0.0	0.53^{Ac} ± 0.00
	2016_2	5.81^{Bc} ± 0.1	0.50^{ABc} ± 0.01	11.16^{Aa} ± 0.8	0.50^{ABc} ± 0.01
SO4	2015_1	9.47^{Ab} ± 0.1	0.60^{Cb} ± 0.01	9.88^{Ba} ± 0.1	0.59^{Cb} ± 0.00
	2015_2	14.92^{Aa} ± 0.8	0.63^{Aa} ± 0.01	8.36^{Ba} ± 1.2	0.63^{Aa} ± 0.02
	2016_1	3.93^{Ad} ± 0.4	0.49^{Bc} ± 0.02	3.95^{Ab} ± 0.2	0.49^{Bc} ± 0.00
	2016_2	7.46^{Bc} ± 0.0	0.50^{ABc} ± 0.01	8.60^{Aa} ± 1.2	0.50^{ABc} ± 0.01
Rootstock per harvest	Sig.	**	ns	**	***
Harvest date	Sig.	***	ns	***	***
Rootstock vs harvest	Sig.	***	*	***	***
Rootstock per semester	Sig.	ns	ns	ns	*
Semester	Sig.	***	ns	***	*
Rootstock vs semester	Sig.	ns	ns	ns	*
Clonal origin group	Sig	ns	ns		

Means followed by different uppercase or lowercase letters within the same column indicate significant differences between rootstocks in the same harvest (uppercase) or across harvests for the same rootstock (lowercase), according to Tukey's 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).

Monomeric anthocyanins in grape berries

As shown in Table 6, the concentration of monomeric anthocyanins in grape skins varied significantly with harvest season, rootstock, and their interaction in both the Portuguese and Spanish clones. In general, higher concentrations were observed during the warmer second semesters, suggesting enhanced anthocyanin biosynthesis under increased thermal amplitude and radiation. Rootstock effects were season-dependent, indicating that the magnitude of anthocyanin accumulation was modulated by rootstock–scion interactions under contrasting environmental conditions.

Total individual molecular anthocyanin content was consistently higher during the second semesters (2015_2 and 2016_2), particularly in grapes grafted onto SO4 and IAC572, reinforcing the known effect of thermal amplitude and radiation in promoting anthocyanin biosynthesis under tropical conditions (De Oliveira *et al*., 2018, 2019a, 2019c, 2020; Rodas *et al*., 2023; Maniero *et al*., 2025).

Among non-acylated forms, malvidin-3-*O*-glucoside was the predominant anthocyanin across all combinations, often exceeding 70 mg/L in the most favourable harvests, followed by petunidin and peonidin derivatives. Spanish clones tended to accumulate higher total anthocyanin concentrations, especially in 2015_2 and 2016_2, reaching values above 230 mg/L with SO4, while Portuguese clones showed greater seasonal fluctuation (Table 6).

The acetylated and coumaroylated derivatives, although present in lower concentrations, also varied significantly between rootstocks and seasons. These forms are known to influence colour stability and hue in red wines, and their seasonal modulation reflects the influence of climatic variables on acyltransferase activity.

Statistical analysis confirmed highly significant effects for harvest ($p < 0.0001$), rootstock × harvest interaction ($p < 0.0001$) and cultivar ($p < 0.001$) for most anthocyanins. These results confirm the importance of selecting rootstock–scion combinations that optimise anthocyanin accumulation in response to tropical environmental conditions, as previously discussed by Clingeleffer *et al*. (2019, 2022), Zombardo *et al*. (2020) and Carvalho *et al*. (2020).

Multivariate analysis of grape composition - PCA

As illustrated in Fig. 4, principal component analysis (PCA) revealed a clear separation of grape samples from Portuguese and Spanish clones, based on physicochemical traits measured over four consecutive harvests under tropical conditions. The first principal components explained a substantial proportion of the total variance, primarily associated with differences in phenolic composition and acidity parameters. This separation indicates that clonal genetic background was a major determinant of grape composition, although seasonal variation also contributed to the observed dispersion pattern.

In Fig. 4A, the first two principal components explained 66.6% of the total variance (PC1: 50.5%, PC2: 16.1%), indicating a strong multivariate response of grape composition to seasonal effects. PC1 predominantly separated samples according to harvest date, highlighting the impact of intra-annual climatic variability on grape ripening and metabolite accumulation. Grapes harvested in 2016 were clearly grouped in the positive PC1 space, with 2016_1 characterised by higher total acidity, malic acid and lower-molecular-weight tannins (monomeric and oligomeric), while 2016_2 showed strong contributions from all tannin fractions. In contrast, 2015 samples occupied the negative PC1 axis, associated with higher °Brix, pH, tartaric acid, non-flavonoids and colour intensity, especially pronounced in 2015_2. In 2015_1, total phenols and anthocyanins were also important contributors.

The PC2 further discriminated harvests, with positive scores reflecting variables such as tartaric acid (2015), colour tonality (2016_2) and total acidity (2016_1), whereas the negative quadrant grouped traits such as non-flavonoids and colour intensity (2015), and phenolic maturity parameters (flavonoids, tannins, and anthocyanins) in 2016_2. These results confirm that grape composition is largely shaped by seasonally dependent thermal amplitude and radiation, as previously demonstrated in tropical systems (De Oliveira *et al*., 2019a,b,c; Rodas *et al*., 2023; Maniero *et al*., 2025).

In Fig. 4B, which isolates data from harvest 2016_1, the PCA captured 62.0% of the total variance (PC1: 40.0%, PC2: 22.0%), showing a clear discrimination between the two clonal origin groups. Aragonez samples were positioned in the positive PC1 quadrant, strongly associated with °Brix, pH, non-flavonoids, tartaric acid, colour tonality and total acidity, indicators of technological ripeness and acid balance. In contrast, Tempranillo samples (Spanish clones) were distributed in the negative PC1 and PC2 quadrants, characterised by higher levels of malic acid, total phenolics, anthocyanins, colour intensity, flavonoids, and all condensed tannin fractions, reflecting a profile of enhanced phenolic and colour maturity.

These multivariate results reinforce the outcomes obtained from univariate analyses (Tables 2 to 6), confirming that both seasonal factors and clonal origin play significant roles in shaping grape composition under tropical conditions. The PCA also highlights the significance of rootstock selection,

TABLE 5 Tannins and tanning power in grapes from Portuguese and Spanish clones of Aragonez (syn. Tempranillo) by rootstock in a tropical semi-arid region, Northeast Brazil.

		Grapes from Portuguese clones					Grapes from Spanish clones				
		Flavan-3-ols / Condensed tannins (mg/g fresh weight of grape)				Tanning power (NTU/mL)	Flavan-3-ols / Condensed tannins (mg/g fresh weight of grape)				Tanning power (NTU/mL)
Rootstock	Harvest	Monomeric	Oligomeric	Polymeric	Total tannins		Monomeric	Oligomeric	Polymeric	Total tannins	
P1103	2015_1	0.44^{Ac} ± 0.04	1.69^{Ab} ± 0.03	40.97^{Ac} ± 0.01	43.12^{Ac} ± 0.01	60.04^{Ab} ± 1.70	0.70^{Abc} ± 0.03	2.60^{Ac} ± 0.03	50.65^{Ac} ± 0.02	53.96^{Ac} ± 0.02	178.46^{Aa} ± 1.40
	2015_2	0.23^{Ac} ± 0.00	0.75^{Bc} ± 0.05	47.16^{Abc} ± 0.00	48.16^{Abc} ± 0.04	53.42^{Ab} ± 1.40	0.30^{Ac} ± 0.01	0.93^{Ad} ± 0.02	41.86^{ABc} ± 0.01	43.10^{ABc} ± 0,01	32.82^{Cc} ± 1.90
	2016_1	1.61^{ABa} ± 0.30	2.20^{Bb} ± 0.01	53.84^{Ab} ± 0.03	57.66^{Bb} ± 0.03	61.10^{Ab} ± 1.90	4.95^{Aa} ± 0.80	8.01^{Aa} ± 0.01	70.96^{Bb} ± 0.01	83.93^{Bb} ± 0.02	80.05^{Ab} ± 1.80
	2016_2	1.10^{Cb} ± 0.20	2.96^{Ba} ± 0.08	86.86^{Aa} ± 0.05	90.93^{ABa} ± 0.05	118.82^{Aa} ± 1.60	1.15^{Ab} ± 0.10	3.97^{Ab} ± 0.01	99.80^{Aa} ± 0.04	104.92^{Aa} ± 0.04	45.61^{Bc} ± 2.20
IAC313	2015_1	0.19^{Ac} ± 0.01	1.85^{Ac} ± 0.04	44.25^{Ab} ± 0.01	46.30^{Ab} ± 0.03	54.00^{Ab} ± 1.30	0.44^{Ac} ± 0.05	2.07^{Ac} ± 0.03	49.53^{Ac} ± 0.00	52.04^{Ab} ± 0.02	109.53^{Ba} ± 2.10
	2015_2	0.32^{Ac} ± 0.01	1.33^{Ac} ± 0.04	32.19^{Bc} ± 0.00	33.85^{Bc} ± 0.00	52.52^{Abc} ± 1.60	0.31^{Ac} ± 0.05	1.30^{Ac} ± 0.02	54.86^{Ac} ± 0.01	56.48^{Ab} ± 0.01	89.00^{Aa} ± 2.10
	2016_1	1.95^{Aa} ± 0.10	3.59^{Ab} ± 0.04	63.82^{Aa} ± 0.02	69.38^{Aa} ± 0.01	32.40^{Cc} ± 1.10	3.93^{Ba} ± 0.70	5.86^{Ca} ± 0.05	71.52^{ABb} ± 0.02	81.31^{ABa} ± 0.01	89.87^{Aa} ± 2.20
	2016_2	1.34^{Cb} ± 0.20	4.33^{Aa} ± 0.02	73.39^{Ba} ± 0.03	79.07^{Ca} ± 0.01	87.80^{Ba} ± 1.90	1.30^{Ab} ± 0.20	3.38^{ABb} ± 0.03	87.82^{ABa} ± 0.05	92.50^{ABa} ± 0.04	53.25^{Bb} ± 1.70
IAC572	2015_1	0.31^{Ac} ± 0.05	2.21^{Ac} ± 0.01	40.97^{Ac} ± 0.03	45.02^{Ac} ± 0.02	19.26^{Bb} ± 1.80	0.42^{Abc} ± 0.08	2.50^{Ab} ± 0.01	44.24^{Ab} ± 00.2	47.17^{Ab} ± 0.01	118.20^{Ba} ± 1.80
	2015_2	0.27^{Ac} ± 0.02	1.09^{ABd} ± 0.02	31.91^{Bd} ± 0.01	33.28^{Bd} ± 0.03	60.43^{Aa} ± 1.90	0.16^{Ac} ± 0.02	0.70^{Ac} ± 0.01	31.74^{Bb} ± 0.00	32.62^{Bb} ± 0.01	79.43^{ABb} ± 1.90
	2016_1	1.63^{ABb} ± 0.30	3.24^{Ab} ± 0.05	61.98^{Ab} ± 0.01	66.86^{ABb} ± 0.03	62.41^{Aa} ± 1.30	4.86^{Aa} ± 0.40	7.10^{ABa} ± 0.01	78.88^{ABa} ± 0.04	90.85^{ABa} ± 0.02	70.38^{Ab} ± 2.40
	2016_2	2.25^{Ba} ± 0.10	4.47^{Aa} ± 0.08	74.18^{Ba} ± 0.02	80.91^{BCa} ± 0.02	65.67^{Ca} ± 1.90	0.83^{Ab} ± 0.03	2.92^{Bb} ± 0.01	83.42^{Ba} ± 0.05	87.19^{Ba} ± 0.03	59.32^{Bb} ± 1.80
SO4	2015_1	0.41^{Ac} ± 0.04	2.17^{Ab} ± 0.03	48.79^{Ac} ± 0.01	51.39^{Ac} ± 0.03	72.20^{Aa} ± 0.90	0.46^{Ac} ± 0.03	1.93^{A} ± 0.03	44.41^{Ab} ± 0.06	46.80^{Ab} ± 0.01	85.03^{Ca} ± 0.40
	2015_2	0.21^{Ac} ± 0.00	1.23^{ABc} ± 0.03	37.39^{ABd} ± 0.02	38.84^{ABd} ± 0.01	57.40^{Aab} ± 1.30	0.14^{Ac} ± 0.04	1.04^{A} ± 0.02	38.56^{Bb} ± 0.01	39.75^{Bb} ± 0.02	57.47^{Bb} ± 1.80
	2016_1	1.49^{Bb} ± 0.60	2.13^{Bb} ± 0.07	63.88^{Ab} ± 0.02	67.50^{ABb} ± 0.01	49.80^{ABb} ± 1.10	4.62^{Aa} ± 1.10	6.91^{B} ± 0.06	85.49^{Aa} ± 0.01	97.03^{Aa} ± 0.03	78.07^{Aab} ± 2.10
	2016_2	2.66^{Aa} ± 0.80	4.54^{Aa} ± 0.03	85.81^{Aa} ± 0.04	93.03^{Aa} ± 0.03	70.29^{BCa} ± 1.60	1.15^{Ab} ± 0.30	2.94^{B} ± 0.01	94.64^{ABa} ± 0.02	98.74^{ABa} ± 0.03	97.20^{Aa} ± 1.60

TABLE 5 (CONTINUED)

		Grapes from Portuguese clones					Grapes from Spanish clones				
		Flavan-3-ols / Condensed tannins (mg/g fresh weight of grape)				Tanning power (NTU/mL)	Flavan-3-ols / Condensed tannins (mg/g fresh weight of grape)				Tanning power (NTU/mL)
Rootstock	Harvest	Monomeric	Oligomeric	Polymeric	Total tannins		Monomeric	Oligomeric	Polymeric	Total tannins	
Rootstock per harvest	Sig.	***	***	**	*	***	***	***	ns	ns	ns
Harvest date	Sig.	***	***	***	***	***	***	***	***	***	**
Rootstock vs harvest	Sig.	***	***	***	***	***	**	**	***	***	ns
Rootstock per semester	Sig.	ns	***	ns	*	***	ns	ns	ns	ns	ns
Semester	Sig.	ns	ns	*	*	***	***	***	ns	ns	***
Rootstock vs semester	Sig.	*	ns	*	ns	ns	ns	ns	ns	ns	***
Clonal origin group	Sig	***	***	***	***	***					

Means followed by different uppercase or lowercase letters within the same column indicate significant differences between rootstocks in the same harvest (uppercase) or across harvests for the same rootstock (lowercase), according to Tukey's 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).

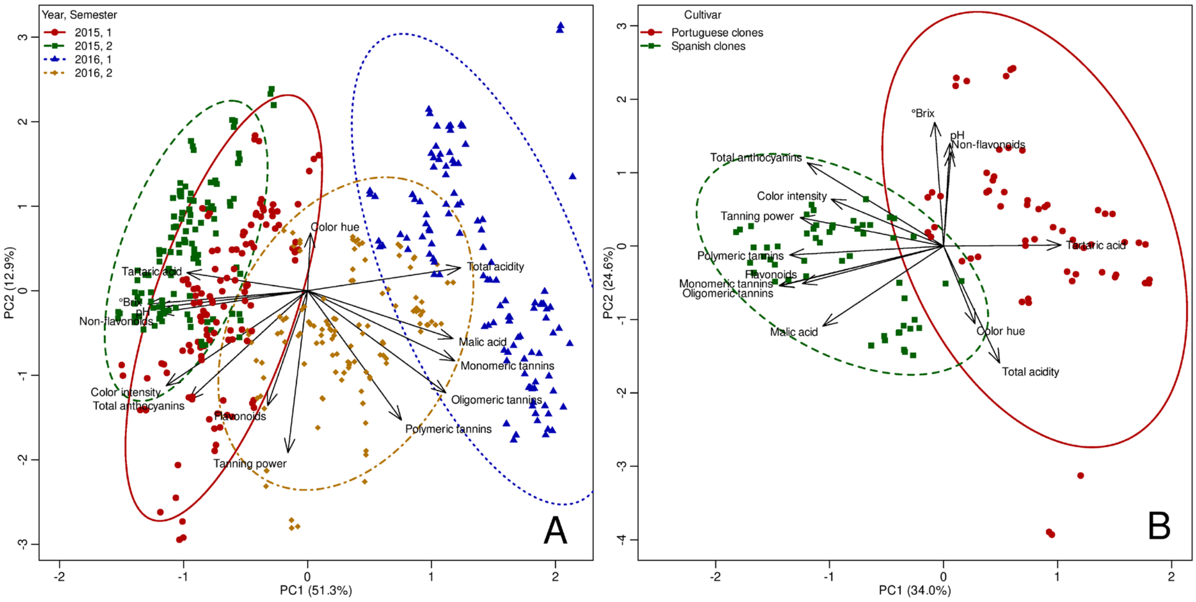

FIGURE 4 Principal component analysis (PCA) of physicochemical and phenolic variables in grapes from Portuguese and Spanish clones of Aragonez (syn. Tempranillo) in Northeast Brazil: (A) across harvests (year, semester), (B) by clone origin.

particularly in humid and low-radiation environments, where phenolic expression can vary substantially due to cultivar-rootstock interactions (Clingeleffer *et al.*, 2019, 2022; Carvalho *et al.*, 2020).

Together, the PCA results confirm that both seasonal and rootstock effects play key roles in determining grape quality attributes under tropical conditions. The clear separation of samples according to harvest period and the clustering associated with specific phenolic and acidity-related variables indicate that environmental factors interact with rootstock–scion combinations to shape grape composition. These findings underscore the need for harvest- and site-specific viticultural strategies in tropical semi-arid regions.

CONCLUSIONS

This study reveals significant differences between Portuguese and Spanish clones of the Aragonez (syn. Tempranillo) cultivar, despite their synonymy. Under the tropical semi-arid conditions of the São Francisco Valley, the performance of these clones varied considerably depending on the rootstock and the timing of the harvest. While yield and berry weight were generally stable across clone-rootstock combinations, marked differences in grape composition, including organic acids, global phenolic parameters, anthocyanins and tannin fractions, were influenced by the interaction of clone, rootstock and harvest season.

Spanish clones, particularly E24 and E51, consistently exhibited superior phenolic and colour attributes, indicating their strong oenological potential for deeply coloured red wines. Among the Portuguese group, 60EAN and 110JBP stood out for their favourable profiles in acidity, anthocyanins and polymeric tannins, supporting their potential for producing balanced wine styles.

The effects of harvest season were particularly significant, with grapes from the second semesters showing higher values for phenolic and colour traits, while the first semesters, often characterised by higher rainfall and shorter ripening cycles, favoured higher acidity and malic acid levels. Rootstock effects were more pronounced under warmer and drier conditions, with SO4 and IAC572 showing consistent advantages in promoting anthocyanin accumulation, phenolic content and tanning potential.

Multivariate analyses (PCA) reinforced these trends, revealing clear groupings according to harvest and clonal origin, and highlighting the complexity of genotype × environment × management interactions. These findings emphasise the importance of strategically selecting rootstock–scion combinations and scheduling harvests according to seasonal conditions to optimise grape quality in tropical viticulture. They also emphasise the importance of clonal diversity as a means of enhancing resilience and tailoring wine styles in emerging warm-climate wine regions.

TABLE 6 Monomeric anthocyanins in grapes from Portuguese and Spanish clones of Aragonez (syn. Tempranillo) by rootstock in a tropical semi-arid region, Northeast Brazil.

Rootstock	P1103				IAC313			
Harvest	2015_1	2015_2	2016_1	2016_2	2015_1	2015_2	2016_1	2016_2
Portuguese clones								
Delphinidin 3-O-glucoside	20.8^{Ab}	25.7^{Cab}	8.8^{Ac}	29.6^{Aa}	24.8^{Aa}	29.1^{BCa}	7.6^{Ab}	28.7^{Aa}
Cyanidin 3-O-glucoside	4.2^{Ba}	3.4^{Ba}	1.1^{Ab}	4.5^{Aa}	4.9^{Ba}	5.0^{Ba}	1.1^{Ab}	5.6^{Aa}
Peonidin 3-O-glucoside	17.1^{Ba}	13.9^{Ba}	6.2^{Ab}	15.0^{Aa}	19.2^{Ba}	16.9^{Ba}	5.7^{Ab}	16.8^{Aa}
Petunidin 3-O-glucoside	12.9^{Ba}	15.1^{Ca}	6.9^{Ab}	14.2^{Aa}	14.1^{ABa}	16.0^{BCa}	5.5^{Ab}	15.0^{Aa}
Malvidin 3-O-glucoside	72.5^{Aa}	76.8^{Aa}	41.0^{ABb}	66.6^{Aa}	77.1^{Aa}	77.5^{Aa}	30.9^{Bc}	62.5^{ABb}
Delphinidin 3-O-acetylglucoside	1.2^{Aa}	1.3^{Aa}	0.5^{Bb}	0.7^{Ab}	1.0^{Aab}	0.9^{Ab}	1.3^{Aa}	0.8^{Ab}
Cyanidin 3-O-acetylglucoside	0.5^{Bb}	0.7^{Aa}	0.5^{Bb}	0.6^{Aab}	0.5^{ABab}	0.6^{Aa}	0.3^{Bb}	0.4^{Ab}
Peonidin 3-O-acetylglucoside	0.8^{Aa}	0.8^{Ba}	0.4^{Ab}	0.9^{Aa}	0.1^{Bc}	0.8^{Bab}	0.5^{Ab}	0.9^{Aa}
Petunidin 3-O-acetylglucoside	0.4^{BCa}	0.5^{Ba}	0.3^{Aa}	0.6^{Aa}	0.2^{Cb}	0.6^{ABa}	0.4^{Aab}	0.5^{Aa}
Malvidin 3-O-acetylglucoside	5.3^{Aa}	0.1^{Ab}	0.3^{Ab}	0.1^{Ab}	4.9^{Aa}	0.1^{Ab}	0.1^{Ab}	0.1^{Ab}
Delphinidin 3-O-coumarylglucoside	3.0^{ABc}	7.7^{Aa}	6.3^{Ab}	6.4^{Aab}	2.3^{Bc}	7.5^{Aa}	4.5^{Bb}	5.8^{ABb}
Peonidin 3-O-coumarylglucoside	0.8^{Aa}	0.5^{Bab}	0.2^{Ab}	0.5^{Ba}	0.8^{Aa}	0.6^{ABa}	0.2^{Ab}	0.5^{Bab}
Petunidin 3-O-coumarylglucoside	1.8^{Aa}	0.5^{Bbc}	0.2^{Ac}	0.7^{Ab}	1.0^{Ba}	0.8^{ABab}	0.2^{Ac}	0.6^{Abc}
Malvidin 3-O-coumarylglucoside	7.4^{Aa}	5.3^{Ab}	2.2^{Ad}	3.9^{Ac}	7.5^{Aa}	5.3^{Ab}	1.4^{Bd}	2.8^{Bc}
Total	148.7^{Aa}	152.3^{Ba}	74.9^{Ab}	144.3^{Aa}	158.4^{Aa}	161.7^{Ba}	59.7^{Ab}	141.0^{Aa}
Spanish clones								
Delphinidin 3-O-glucoside	32.6^{Ba}	40.0^{Aa}	11.9^{Ab}	39.2^{ABa}	29.5^{Bb}	42.0^{Aa}	13.4^{Ac}	33.6^{Bab}
Cyanidin 3-O-glucoside	8.7^{Ba}	7.2^{Aab}	1.8^{Ac}	5.9^{ABb}	8.2^{Ba}	6.1^{ABab}	2.3^{Ac}	4.9^{Bbc}
Peonidin 3-O-glucoside	20.9^{Ba}	20.9^{Aa}	7.1^{Ab}	17.8^{ABa}	24.8^{Ba}	18.0^{ABb}	8.9^{Ac}	13.8^{BCbc}
Petunidin 3-O-glucoside	15.1^{Bb}	19.6^{Aa}	7.3^{Ac}	19.8^{Aa}	15.5^{Bab}	20.1^{Aa}	7.8^{Ac}	15.4^{BCb}
Malvidin 3-O-glucoside	65.8^{Ab}	78.3^{Aab}	42.9^{Ac}	88.1^{Aa}	74.2^{Aa}	75.8^{Aa}	43.9^{Ab}	74.2^{ABa}
Delphinidin 3-O-acetylglucoside	0.9^{Aa}	0.9^{Aa}	1.1^{Aa}	0.4^{ABb}	0.8^{Aa}	0.7^{Aa}	0.4^{Ba}	0.7^{Aa}
Cyanidin 3-O-acetylglucoside	0.7^{Aa}	0.5^{ABab}	0.4^{Bb}	0.5^{Aab}	0.6^{Aa}	0.4^{Bab}	0.3^{Bb}	0.5^{Aa}
Peonidin 3-O-acetylglucoside	1.2^{Aa}	0.9^{ABa}	0.6^{Ab}	1.2^{Aa}	1.0^{Ba}	0.9^{ABab}	0.7^{Ab}	0.9^{Aab}
Petunidin 3-O-acetylglucoside	0.7^{Ba}	0.7^{Aa}	0.6^{Aa}	0.8^{Aa}	0.7^{Ba}	0.7^{Aa}	0.6^{Aab}	0.4^{Bb}
Malvidin 3-O-acetylglucoside	0.3^{Aa}	0.1^{Ba}	0.1^{Aa}	0.2^{Ba}	0.2^{Ab}	0.6^{Aa}	0.1^{Ab}	0.1^{Bb}
Delphinidin 3-O-coumarylglucoside	7.4^{Ba}	7.2^{Aa}	6.7^{Aa}	7.9^{Aa}	8.2^{Ba}	6.1^{ABb}	6.7^{Aab}	7.3^{ABab}
Peonidin 3-O-coumarylglucoside	0.9^{Ca}	0.5^{ABb}	0.5^{Ab}	0.7^{Ab}	1.1^{ABa}	0.7^{Ab}	0.4^{Ac}	0.6^{Abc}
Petunidin 3-O-coumarylglucoside	0.8^{Ba}	0.6^{Bb}	0.4^{Ac}	0.7^{Aab}	0.8^{Bab}	0.9^{Aa}	0.3^{Ab}	0.6^{ABb}
Malvidin 3-O-coumarylglucoside	4.5^{Ca}	4.7^{Ba}	2.9^{Ab}	4.8^{Aa}	5.7^{Bab}	6.1^{Aa}	2.8^{Ac}	4.8^{Ab}
Total	159.8^{Ba}	182.1^{Aa}	84.3^{Ab}	188.0^{Aa}	171.3^{Ba}	179.1^{Aa}	88.6^{Ab}	157.8^{ABa}

TABLE 6 (CONTINUED)

IAC572				SO4				ANOVA (p-values)				
2015_1	2015_2	2016_1	2016_2	2015_1	2015_2	2016_1	2016_2	R/H	H	RxH	R/S	S
25.6^{Ab}	36.6^{Ba}	11.1^{Ac}	25.5^{Ab}	24.3^{Ab}	45.9^{Aa}	11.1^{Ac}	26.1^{Ab}	***	***	***	ns	***
8.5^{Aa}	7.5^{Aa}	1.5^{Ac}	4.9^{Ab}	4.2^{Bb}	8.6^{Aa}	1.6^{Ac}	4.2^{Ab}	***	***	***	*	***
27.3^{Aa}	23.3^{Aa}	7.4^{Ac}	14.6^{Ab}	17.6^{Bb}	24.4^{Aa}	7.4^{Ad}	12.5^{Ac}	**	***	***	ns	**
16.5^{Aa}	18.7^{Ba}	7.6^{Ac}	13.1^{Ab}	14.2^{ABb}	22.1^{Aa}	8.0^{Ac}	13.7^{Ab}	***	***	***	ns	***
77.8^{Aa}	74.6^{Aa}	43.4^{Ab}	53.4^{Bb}	80.1^{Aa}	86.7^{Aa}	43.7^{Ad}	64.9^{Abc}	***	***	***	ns	***
1.2^{Aa}	1.2^{Aa}	0.6^{Bb}	0.7^{Ab}	1.3^{Aa}	1.1^{Aab}	0.7^{Bbc}	0.5^{Ab}	***	***	***	**	ns
0.7^{Aa}	0.6^{Aa}	0.7^{Aa}	0.5^{Aa}	0.4^{Bb}	0.6^{Aa}	0.4^{Bab}	0.4^{Aab}	***	***	***	ns	ns
0.9^{Aa}	0.8^{Bab}	0.6^{Ab}	0.8^{Aab}	0.6^{Ab}	1.2^{Aa}	0.6^{Ab}	0.9^{Aab}	***	***	***	*	*
0.9^{Aa}	0.3^{Bb}	0.5^{Ab}	0.4^{Ab}	0.7^{ABab}	0.8^{Aa}	0.5^{Ab}	0.6^{Aab}	***	***	***	ns	ns
2.9^{Aa}	0.1^{Ab}	0.1^{Ab}	0.1^{Ab}	5.1^{Aa}	0.1^{Ab}	0.1^{Ab}	0.1^{Ab}	***	***	***	ns	***
4.1^{Ab}	5.8^{Ba}	6.0^{Aa}	4.8^{Bab}	2.4^{Bb}	6.9^{ABa}	6.7^{Aa}	6.2^{Aa}	***	***	***	ns	ns
0.8^{Aa}	0.6^{ABab}	0.3^{Ab}	0.4^{Bb}	0.7^{Ab}	0.8^{Aab}	0.3^{Ac}	1.1^{Aa}	***	***	***	ns	ns
1.1^{Ba}	0.6^{Ba}	0.3^{Aa}	0.5^{Aa}	1.7^{Aa}	1.0^{Ab}	0.4^{Ac}	0.6^{Ac}	*	***	***	ns	**
6.8^{Aa}	3.7^{Bb}	2.3^{Ac}	2.2^{Bc}	7.1^{Aa}	5.4^{Ab}	2.6^{Ad}	4.4^{Ac}	***	***	***	ns	ns
175.1^{Aa}	174.4^{Ba}	82.4^{Ac}	121.9^{Ab}	160.4^{Ab}	205.6^{Aa}	84.1^{Ac}	136.2^{Ab}	***	***	***	ns	ns
36.3^{ABa}	37.4^{Aa}	12.5^{Ab}	45.2^{Aa}	41.9^{Aa}	22.6^{Bb}	10.5^{Ac}	23.0^{Cb}	***	***	***	ns	***
12.4^{Aa}	6.2^{ABb}	1.7^{Ac}	7.6^{Ab}	12.8^{Aa}	4.4^{Bb}	1.7^{Ac}	3.5^{Bbc}	***	***	***	***	ns
42.8^{Aa}	19.4^{Ab}	7.8^{Ac}	20.0^{Ab}	39.6^{Aa}	13.4^{Bb}	6.4^{Ac}	11.3^{Cbc}	***	***	***	*	***
20.2^{Aa}	18.4^{Aa}	7.9^{Ab}	19.5^{ABa}	22.0^{Aa}	12.3^{Bb}	6.3^{Ac}	12.0^{Cb}	**	***	***	ns	***
93.7^{Aa}	74.4^{Ab}	46.1^{Ac}	83.2^{Aab}	98.5^{Aa}	57.1^{Bb}	36.6^{Ac}	62.5^{Bb}	***	***	***	ns	***
0.9^{Aa}	0.8^{Aa}	0.3^{Bb}	0.3^{Bb}	0.9^{Aa}	0.7^{Aa}	0.1^{Bb}	0.3^{Bb}	***	***	***	ns	**
0.7^{Aab}	0.7^{Aab}	0.8^{Aa}	0.5^{Ab}	0.6^{Aab}	0.8^{Aa}	0.4^{Bb}	0.5^{Ab}	***	***	***	*	ns
1.6^{Aa}	1.1^{Ab}	0.6^{Ac}	0.9^{Ab}	1.6^{Aa}	0.8^{Bb}	0.5^{Ab}	0.6^{Bb}	***	***	***	***	ns
0.8^{Ba}	0.8^{Aa}	0.5^{Ab}	0.6^{ABab}	1.1^{Aa}	0.7^{Ab}	0.5^{Ab}	0.6^{ABb}	***	***	***	**	ns
0.4^{Ab}	0.1^{Bb}	0.1^{Ab}	0.8^{Aa}	0.4^{Aa}	0.2^{Aa}	0.1^{Aa}	0.1^{Ba}					
10.9^{Aa}	6.5^{ABb}	6.8^{Ab}	5.9^{BCb}	10.3^{Aa}	5.3^{Bb}	5.8^{Ab}	5.8^{Cb}	***	***	***	**	ns
1.5^{Aa}	0.6^{ABb}	0.3^{Ac}	0.7^{Ab}	1.2^{Ba}	0.4^{Bb}	0.3^{Ab}	0.5^{Ab}	***	***	***	ns	***
1.0^{Aa}	0.7^{ABb}	0.3^{Ac}	0.7^{Ab}	1.0^{Aa}	0.6^{Bb}	0.3^{Ac}	0.5^{Bbc}	ns	***	***	ns	*
7.4^{Aa}	4.5^{BCb}	2.7^{Ac}	4.4^{ABb}	6.8^{Aa}	3.5^{Cb}	2.6^{Ab}	3.6^{Bb}	ns	***	ns	ns	ns
230.6^{Aa}	171.6^{Ab}	88.4^{Ac}	190.3^{Ab}	238.7^{Aa}	122.8^{Bb}	72.1^{Ac}	124.8^{Bb}	ns	***	ns	ns	ns

Means followed by different uppercase or lowercase letters within the same row indicate significant differences between rootstocks in the same harvest (uppercase) or across harvests for the same rootstock (lowercase), according to Tukey's 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).

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