DOI: https://doi.org/10.20870/oeno-one.2024.58.3.8123

OPEN ACCESS

ORIGINAL RESEARCH ARTICLE

Exploring intra-specific variability as an adaptive strategy to climate change: Response of 21 grapevine cultivars grown under drought conditions

A. Sergio Serrano[1,2], Jesús Martínez-Gascueña[1], Gonzalo L. Alonso[2], Cristina Cebrián-Tarancón[2], Adela Mena Morales[1] and Juan L. Chacón-Vozmediano[1,*]

[1] Regional Institute of Agri-Food and Forestry Research and Development of Castilla-La Mancha (IRIAF), Ctra. Toledo-Albacete s/n, 13700 Tomelloso, Spain
[2] Department of Agricultural Chemistry, School of Agricultural and Forestry Engineering and Biotechnology, University of Castilla-La Mancha, Avda. de España s/n, 02071 Albacete, Spain

*correspondence:
jlchacon@jccm.es

Associate editor:
Franco Meggio

Received:
15 May 2024
Accepted:
8 August 2024
Published:
12 September 2024

ABSTRACT

In recent decades, as a consequence of climate change, grape ripening is occurring under warmer and drier conditions, resulting in losses in the yield and quality of wine grapes. Several alternatives may reduce these negative effects. One that stands out for its potential for long-term adaptation is the selection of better-adapted plant material. For this purpose, during two consecutive years, several agronomic and quality parameters were recorded in 21 grapevine cultivars grown under two water stress levels (moderate and severe). The results revealed that some cultivars considered a minority, as well as others recently recovered from the viticultural heritage that had almost become extinct, could offer a similar and even better response to drought than other widespread cultivars. In particular, Maquías, Montonera del Casar, and Tortozona Tinta stood out for their high total acidity; Tinto Fragoso and Tinto Velasco for their high anthocyanin concentration; and Albillo Dorado and Moscatel Serrano for their high varietal aromatic potential. These cultivars could contribute to diversifying varietal offerings and to maintaining the sustainability of the wine sector in the coming decades.

KEYWORDS: Carbon isotope ratio, grape quality, recovered grapevine cultivars, sustainable viticulture, vigour, water stress, yield

INTRODUCTION

Grapevines have traditionally been grown in semi-arid areas because they are considered a drought-tolerant species (Chaves *et al*., 2010; Zarrouk *et al*., 2015). Furthermore, it is known that, within this species, moderate water stress at certain times of the season improves the berry quality traits and, as a consequence, the quality of wines. On the contrary, when water stress is severe and sustained over time, it is detrimental to both yield and quality (Alatzas *et al*., 2021). Water stress affects the yield, particularly the berry size (Alatzas *et al*., 2021; Chacón-Vozmediano *et al*., 2020; Junquera *et al*., 2012; Mirás-Avalos and Intrigliolo, 2017; Williams *et al*., 2010; Zufferey *et al*., 2020), the vigour of vines (Chacón-Vozmediano *et al*., 2020; Zufferey *et al*., 2018, 2020), and the grape quality (Alatzas *et al*., 2021; Chacón-Vozmediano *et al*., 2021; Zufferey *et al*., 2018, 2020). However, not all grapevine cultivars are affected by drought in the same way. Fortunately, the high genetic diversity that exists among grapevines represents an advantage when selecting those that, due to their drought-tolerant traits, are most suitable for each growing area (van Leeuwen *et al*., 2019), considering the water availability and edaphoclimatic conditions of the given location. Among grapevine cultivars, those of a minority crop as well as others that were recently recovered after being on the verge of extinction are particularly interesting, both for representing an important heritage and for their significant potential in the search for tolerance traits to face future climatic conditions (Antolín *et al*., 2022; Florez-Sarasa *et al*., 2020; Gisbert *et al*., 2022; Muñoz-Organero *et al*., 2022).

The carbon isotope ratio ($\delta^{13}C$) is considered an integral marker of the vine water status during berry growth, particularly during the period from veraison to harvest (Bchir *et al*., 2016; Brillante *et al*., 2020; Santesteban *et al*., 2015). In the context of plant physiology studies, it is a relatively quick and easy measure, which may be performed only once per season, providing a more complete estimate of the plant's water status with respect to point measurements —such as water potential and gas exchange—(Brillante *et al*., 2020). Therefore, it may be used to establish "a posteriori" the vine water status in a global way. When grapevines experience water deficit, stomatal closure is enhanced, and, as a consequence, the $^{13}C/^{12}C$ ratio increases. This is because, under water stress conditions, there is less discrimination of the ^{13}C form because its diffusion through the stomata is prevented and also because it is less reactive against the enzyme ribulose-1.5-bisphosphate carboxylase-oxygenase (RuBisCo) than ^{12}C (Farquhar *et al*., 1989; Mateo *et al*., 2004).

This work aimed to study the behaviour of 21 grapevine cultivars in terms of yield, vigour, and grape quality when grown under moderate and severe water stress conditions in an area with a semi-arid Mediterranean climate. Identifying cultivars capable of simultaneously maintaining moderate yields and good quality traits under drought conditions may be of great help for the sustainability of viticulture in areas that are increasingly threatened by the impacts of climate change.

MATERIALS AND METHODS

1. Experimental site, plant material, phenology, and growing conditions

The study was conducted in a multivarietal experimental vineyard (latitude: 39°10'14" N, longitude: 3°00'16" W, altitude: 660 m.a.s.l.) located at the Regional Institute of Agri-Food and Forestry Research and Development of Castilla-La Mancha (IRIAF), in Tomelloso, Spain, from 2021 to 2022.

TABLE 1. List of 21 studied grapevine cultivars, including their common name and Vitis International Variety Catalogue (VIVC) code.

Representativeness	Red grape		White grape	
	Name	VIVC code	Name	VIVC code
Widespread cultivars	Bobal	1493	Airén	157
	Garnacha Tinta	4461	Chardonnay	2455
	Merlot	7657	Macabeo	13127
	Syrah	11748	Riesling	10077
Minority/recovered cultivars	Moravia Agria	7376	Albillo Dorado	23429
	Tinto Fragoso	24144	Azargón	24631
	Tinto Velasco	17353	Blanca del Tollo	25058
	Tortozona Tinta	24145	Jarrosuelto	24138
			Maquías	24139
			Mizancho	25060
			Montonera del Casar	24140
			Moscatel Serrano	17493
			Pintada	24142

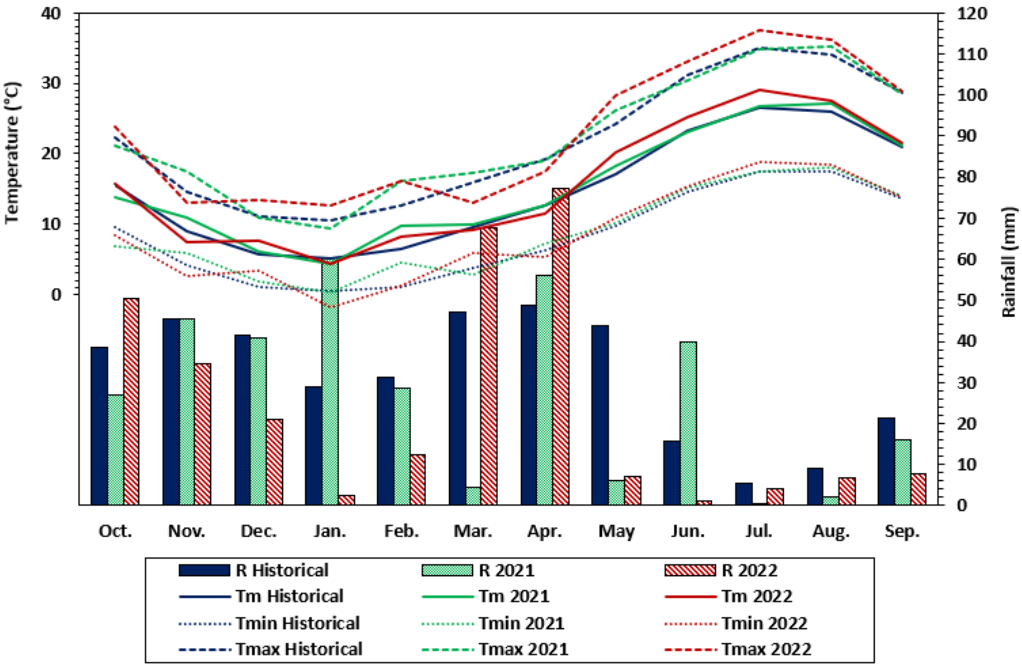

FIGURE 1. Total rainfall (R, bars) and monthly average temperatures (lines): average of averages temperature (T_m), average of minimums temperature (T_{min}), and average of maximums temperature (T_{max}). Data for the agronomic years 2021 and 2022 were collected from the Davis station located in the study plot, whereas historical data for 20 years (2001–2020) were collected from the SIAR station located in Argamasilla de Alba.

Twenty-one cultivars—eight widespread and 13 minority/recovered—were included in this work (Table 1). Cultivars were arranged in parallel rows, with each row consisting of 50 vines (1 row per cultivar), oriented at 30°NNE–210°SSW. Vines, aged 13 years, were grafted onto Fercal rootstock and trained using the VSP trellis system and bilateral Royat Cordon pruning with six two-bud spurs per vine. The cordon height, measured from the soil surface, was set at 0.9 m. The planting frame consisted of a row spacing of 2.8 m and a vine spacing of 1.2 m (2,976 vines ha^{-1}).

The vineyard is placed on Petrocalcic Calcixerept soil (USDA soil classification) with a sandy loam texture and contains 16 % active limestone and 2 % organic matter. Its depth reaches 30 cm, beyond which lies an impenetrable petrocalcic horizon that restricts vine roots. This soil type is widely found in the La Mancha wine region and has a longstanding association with grapevine growing. The topography of the study plot is flat and the soil pedoclimatic conditions reflect the typical xeric moisture regime of Mediterranean climates. To maintain soil fertility, organic pellets were applied annually at a rate of 1,200 kg ha^{-1} along the planting rows. The vineyard soil was managed mechanically by mowing the permanent natural plant cover throughout the year.

The climate in the area is classified as semi-arid continental Mediterranean, characterised by hot and dry summers, as well as cold and moderately rainy winters. Historical climate data from 2001 to 2020, recorded at the Argamasilla de Alba weather station located 12 km from the experimental site, were utilised to characterise the climate conditions. This weather station belongs to the SIAR network, operated by the Spanish Ministry for Agriculture, Fisheries, and Food (MAPA). The region experiences a significant annual temperature range, with a thermal amplitude of 21.5 °C. The average annual temperature is 14.8 °C, and the reference evapotranspiration (ET_o) is 1,290 mm, whereas the annual rainfall amounts to 377 mm. Usually, only 40 % of the total rainfall occurs during the grapevine growing season. The dry season is quite lengthy, lasting approximately 4.5 months according to Gaussen and Bagnouls (1953) methodology. The Huglin index for the area is 2,740, indicating a warm climate classification (HI_{+2}) (Huglin, 1978). Throughout the study period, the climate data were collected by a weather station located within the study plot (Davis Vantage Pro 2™ Groweather®, Davis instruments, Hayward, CA, USA). Figure 1 demonstrates the monthly rainfall and average air temperatures at the study site during the two agronomic years of the study alongside the 20-year averages (2001–2020).

The phenology of cultivars was monitored, noting the dates of the main phenological stages according to the BBCH scale (Lorenz *et al*., 1995): budbreak (07), flowering (65), veraison (81), and ripeness (89). The phenological stage dates were assigned when 50 % of the buds or clusters of the monitored vines reached that stage, except for ripeness, whose date was assigned when 100 % of the grapes were ripe. The phenology dates for each cultivar and the cycle length—from budbreak to ripeness—are included in the Supplementary Material (Table S1).

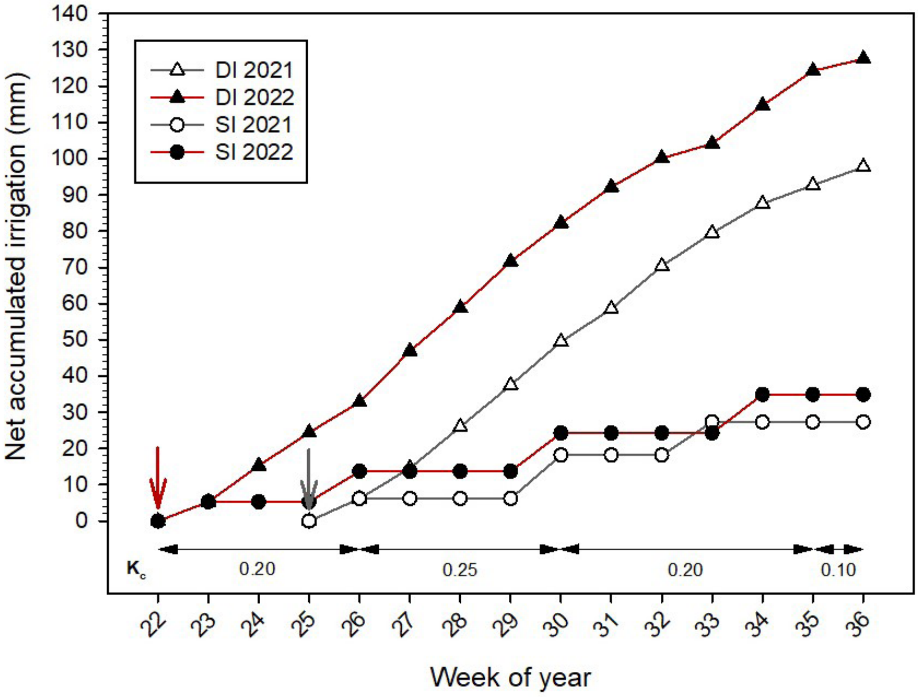

FIGURE 2. Accumulated irrigation amounts per week for each water regime and year. Grey and red arrows indicate the onset of irrigation for 2021 and 2022 years, respectively. Notes: DI: moderate water stress; SI: severe water stress.

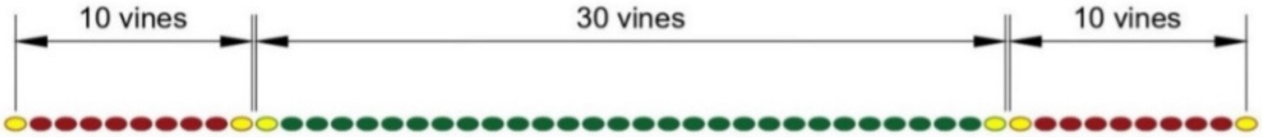

FIGURE 3. Irrigation design scheme. Green dots represent the vines grown under a DI regime and red dots represent the vines grown under a SI regime. Yellow dots represent the buffer vines.

The vineyard was managed under two different drought levels. One of the irrigation patterns was aimed to maintain the vines under moderate water stress conditions by deficit irrigation (–25 ‰ < must $\delta^{13}C$ < –24 ‰, DI regime), whereas the other was aimed to induce severe water stress by "survival" irrigation (must $\delta^{13}C$ > –24 ‰, SI regime). Irrigation was calculated using the water balance method (Allen *et al.*, 2006), based on data (ET_o and rainfall) obtained from the weather station located in the experimental vineyard. In the DI regime, a percentage (K_c, Figure 2) of the ET_o accumulated the previous week was replaced weekly, whereas, in the SI regime, the replacement was every 3–4 weeks, when the drought effects began to become evident in vines—for example, wilting and defoliation—and only to ensure the survival of the vines. In 2021, irrigation started in the fifth week of June, whereas in 2022 it started the second week of June. In both years, irrigation ended the second week of September. Figure 2 demonstrates the weekly accumulated irrigation amounts for each water regime and year.

Previously this study, all vines were managed under irrigation with a K_c of 0.25. However, during the two years of the study, an irrigation design was adopted so that the 10 vines at the ends of the row for each cultivar were grown under a SI regime, and the 30 central vines under a DI regime (Figure 3). The vines located at the ends of each water regime were not considered in the study (buffer vines). An on-surface drip irrigation system with self-compensating drippers, spaced at 0.6 m within the plant row, and with a nominal flow rate of 2.2 L h^{-1} was used. A water application efficiency of 95 % was considered. Irrigation was conducted at night to minimise evaporation losses.

2. Yield, pruning weight, and Ravaz index

To determine the harvest date of each cultivar, regular sampling was performed until the grapes reached a concentration of total soluble solids between 22.5 and 24.5 °Brix for red cultivars, and between 20 and 22 °Brix for white cultivars. Five vines were harvested per water regime ($n = 5$). From the remaining vines of each water regime, a representative sample of 1.5 kg of clusters was harvested and frozen for subsequent grape quality analysis. Yield (kg vine^{-1}) was measured in each vine. Vines were pruned in winter and pruning weight (kg vine^{-1}) was assessed for each monitored vine. To assess the balance between yield and vigour, the Ravaz index was calculated for these same vines.

3. Must physicochemical parameters and grape quality analysis

The grapes of each harvested vine were individually crushed with a manual roller crusher to extract the must. Following the official methods of the International Organisation of Vine and Wine (OIV, 2024), total soluble solids of must (°Brix) were measured by electronic refractometry, total acidity (g L^{-1}) and pH by potentiometry, and potassium (mg L^{-1}) by atomic absorption spectrophotometry. The must was sampled (12 mL per vine) and frozen in polycarbonate test tubes for subsequent carbon isotopic composition analysis (δ^{13}C).

To analyse the grape phenolic potential, the methodology described below was followed. An aqueous solution of 0.1 N HCl at pH 1 was prepared as reactive. From each defrosted grape sample, 200 berries randomly selected were taken and crushed at 323 RCF until the dough was homogeneous. 50 g of the triturate was weighed into a centrifuge bottle and 50 mL of aqueous solution at pH 1 was added. The flask after being covered, was shaken for a few seconds to homogenise the content and left to macerate for 24 h at room temperature in the laboratory. After this time, it was centrifuged for 10 min at 3,279 RCF. In the extract obtained, the total polyphenol index (Ribéreau-Gayon *et al*., 1982), colour intensity (Glories, 1984), and anthocyanins (Ribéreau-Gayon and Stronestreet, 1965) were analysed. All parameters were determined in duplicate.

To assess the glycosylated precursors of varietal aromatic compounds, the varietal aroma potential index (IPAv) was determined in duplicate from defrosted grapes following the method described by Serrano de la Hoz *et al*. (2014). The method, based on Salinas *et al*. (2012), is a spectrophotometric determination of the glucose released from the glycosylated aroma precursors via acid hydrolysis.

4. Must carbon isotope ratio analysis

The carbon isotope composition of grape must was measured by online analysis using a ThermoQuest Flash 1112 Elemental Analyser equipped with an autosampler and coupled to a Delta-Plus IRMS (ThermoQuest, Bremen, Germany) through a ConFlo III interface (ThermoQuest). One microlitre of the must was placed in a tin capsule and sealed. All of the carbon in the sample was oxidised to CO_2 by the reactors of the elemental analyser. The analyser passed the gas through a gas chromatography (GC) column to separate the CO_2 from other gases and then brought the CO_2 into the mass spectrometer by a helium flow. The carbon isotope composition was expressed as (1):

$$\delta^{13}C = \left[\left(\frac{R_s}{R_{std}}\right) - 1\right] 1{,}000 \qquad (1)$$

where R_s is the $^{13}C/^{12}C$ ratio of the sample and R_{std} is the international reference standard Vienna Pee Dee Belemnite (VPDB). For each cultivar, five vines per water regime were sampled.

5. Statistical analysis

The data were analysed using analysis of variance (ANOVA, $\alpha = 0.05$) and averages were separated by Duncan's multiple range test using Statgraphics Centurion XVIII software (Statgraphics Technologies, The Plains, VA, USA). The data from the two years were analysed as a whole, separated by grape colour and water regime. Year × water regime and cultivar × water regime interactions were assessed by two-way ANOVA. The results for the cultivar × water regime interaction are included in the Supplementary Material (Table S2). Principal component analysis (PCA) and cluster analysis were performed to determine cultivar groupings based on multiple variables. Bar graphs were plotted using SigmaPlot 14.0 software (Systat Software, San José, CA, USA).

RESULTS AND DISCUSSION

1. Yield, pruning weight, and Ravaz index

Overall, yield, pruning weight, and the Ravaz index—yield-to-pruning weight ratio—demonstrated highly significant differences ($p < 0.001$) among years and water regimes (Figure 4). Regarding yield, the highest yields were obtained in the DI regime in 2021 (3.22 kg vine^{-1}), whereas the lowest were in the SI regime in 2022 (1.11 kg vine^{-1}), which were half of the yields obtained under the same regime in 2021 (2.21 kg vine^{-1}). Yields in the DI regime in 2022 were similar to those obtained in 2021 under the SI regime (approximately 2.30 kg vine^{-1}). As can be seen, yields were more affected in 2022 compared to 2021, probably due to a warmer summer (Figure 1). As for red cultivars, differences in yields in the DI regime were significantly greater ($p < 0.01$) than in the SI regime ($p < 0.05$). Moravia Agria had the highest yield (3.90 kg vine^{-1}) under the DI regime, whereas Tinto Fragoso had the lowest yield (1.19 kg vine^{-1}). Under the SI regime, most cultivars exhibited yields below 1.40 kg vine^{-1}; this was the case for Merlot, Moravia Agria, Syrah, Tinto Fragoso, and Tortozona Tinta. By contrast, Garnacha Tinta exhibited the highest yield (2.45 kg vine^{-1}). These findings with Merlot were consistent with those previously reported by Chacón-Vozmediano *et al*. (2020), who obtained similar yields in this cultivar under different water stress regimes in the same location; however, the findings in this study were lower than those reported by Munitz *et al*. (2017) in Israel under different deficit irrigation regimes, probably due to the different experimental conditions. Regarding Syrah, the yield obtained in this study under the DI regime was similar to those reported by Korkutal *et al*. (2019) in vines grown in pots under early water stress. In general, yields obtained for Bobal, Garnacha Tinta, Moravia Agria, and Tinto Velasco were lower than those reported by Serrano *et al*. (2022) under

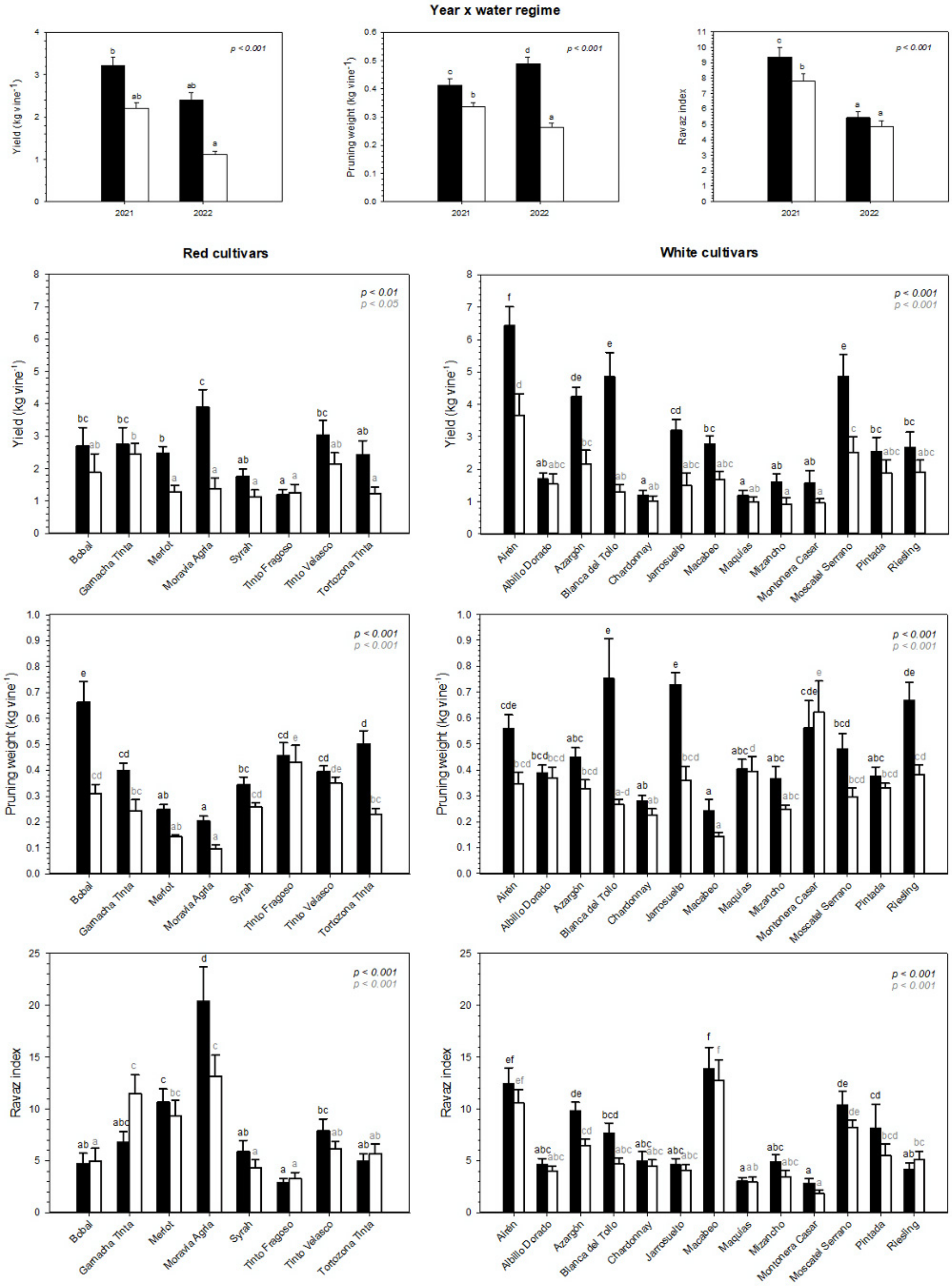

FIGURE 4. Yield, pruning weight, and Ravaz index. Columns and error bars depict averages and standard error, respectively, of 10 samples (5 replicates each year) or 105 samples (year × water regime plots). The black and white columns are values from the DI (moderate water stress) and SI (severe water stress) regimes, respectively. Different letters indicate statistically significant differences among different cultivars or among the different year–water regime combinations (year × water regime plots) by Duncan's test.

a similar water regime to our SI in the same location, which may be due to differences in planting density, planting age, and rootstock used. As for the latter, the rootstock used by these authors (110-R) is usually considered more drought-resistant and more vigorous than the one used by us (Fercal). However, the yield obtained in Bobal under the SI regime was consistent with those reported by Pérez-Álvarez *et al.* (2021) under deficit irrigation. Regarding white cultivars, both the DI and SI regimes demonstrated highly significant differences in yields among different cultivars ($p < 0.001$). Airén stood out as the cultivar with the highest yield in both the DI and SI regimes (6.43 and 3.67 kg vine^{-1}, respectively). In the DI regime, Azargón, Blanca del Tollo, and Moscatel Serrano also were noticeable with yields above 4 kg vine^{-1}, whereas Chardonnay and Maquías exhibited the lowest yields (approximately 1.20 kg vine^{-1}). Most cultivars grown under the SI regime exhibited yields below 2 kg vine^{-1}, and some (Mizancho and Montonera del Casar) even exhibited yields below 1 kg vine^{-1}. Yields obtained in this study under the SI regime for Airén and Macabeo were lower than those reported by Serrano *et al*. (2023) under a similar water regime at the same location, which is likely due to differences in the vineyard characteristics, such as rootstock. Yield responded better to irrigation in cultivars such as Airén, Azargón, Blanca del Tollo, Moravia Agria, and Moscatel Serrano, with increases greater than 2 kg vine^{-1} in the DI regime compared to the SI regime, whereas others such as Albillo Dorado, Chardonnay, and Maquías exhibited similar yields in both water regimes (Table S2), meaning that their yields were not significantly affected by drought conditions.

Several authors have observed a decrease in plant vigour in vines that had been subjected to water restrictions (Chaves *et al*., 2007; Keller *et al*., 2016; Zufferey *et al*., 2018). In our study, vine vigour was assessed by pruning weight. In 2022, DI vines exhibited higher vigour than in 2021, whereas the vigour in the SI regime was lower in 2022 (Figure 4). This year, the differences among water regimes were greater than those seen in 2021, since pruning weight was almost half in the SI regime (0.26 kg vine^{-1}) than in the DI regime (0.49 kg vine^{-1}). In all cases, pruning weight demonstrated highly significant differences among cultivars ($p < 0.001$). Regarding red cultivars, Bobal was the most vigorous cultivar under the DI regime (0.66 kg vine^{-1}), followed by Tortozona Tinta with greater than 0.50 kg vine^{-1}. Tinto Fragoso and Tinto Velasco were the most vigorous cultivars under the SI regime (0.43 and 0.35 kg vine^{-1}, respectively). Moravia Agria and Merlot stood out for having the lowest pruning weight values in both the DI regime (0.21 and 0.25 kg vine^{-1}, respectively) and the SI regime (0.10 and 0.14 kg vine^{-1}, respectively). As for white cultivars, Blanca del Tollo and Jarrosuelto were remarkable as the most vigorous cultivars when grown under the DI regime, with pruning weight values over 0.70 kg vine^{-1}. However, in the SI regime, the most vigorous cultivar was Montonera del Casar (0.62 kg vine^{-1}). In both water regimes, the cultivars exhibiting the lowest vigour were Macabeo (0.24 and 0.14 kg vine^{-1} for the DI and SI regimes, respectively) and Chardonnay (0.28 and 0.23 kg vine^{-1} for the DI and SI regimes, respectively). Among the cultivars whose vigour was most affected by drought were Blanca del Tollo, Bobal, and Jarrosuelto, with a decrease in pruning weight values greater than 0.35 kg vine^{-1} in the SI regime compared to the DI regime. By contrast, the vigour of other cultivars such as Albillo Dorado, Pintada, and Tinto Fragoso was not significantly affected by drought (Table S2).

Considering all samples and both years, the Ravaz index was affected only by the irrigation regime in 2021 (Figure 4). The Ravaz index presented the highest values in 2021 (9.37 and 7.80 in DI and SI vines, respectively). By contrast, in 2022, both water regimes exhibited similar values on the Ravaz index (around 5). Previous studies have reported that a yield-to-pruning weight ratio of 5–10 in warm climates is an indicator of balanced vines capable of producing high-quality grapes (Bravdo *et al*., 1985; Reynolds, 1989; Smart *et al*., 1990). According to these values, vines of most cultivars in both irrigation regimes were unbalanced either due to excess yield compared to pruning weight or vice versa. The Ravaz index exhibited an exceptionally high value in Moravia Agria when grown under the DI regime (20.35), whereas Tinto Fragoso exhibited the lowest value (2.86). Under the SI regime, Moravia Agria and Garnacha Tinta exhibited the highest Ravaz index values (13.17 and 11.49, respectively). By contrast, Bobal, Syrah, and Tinto Fragoso had values lower than or equal to 5. Regarding white cultivars, Airén and Macabeo stood out in both water regimes for exhibiting the highest values on the Ravaz index (over 10), whereas Maquías and Montonera del Casar had the lowest (below 3). Among all cultivars, Albillo Dorado, Chardonnay, Maquías, Montonera del Casar, Pintada, Tinto Fragoso, and Tinto Velasco stood out as the ones that were not significantly affected by water deficit in any of the yield and vigour components analysed (Table S2), meaning a good response to drought conditions.

2. Must physicochemical parameters

Regarding must physicochemical parameters (Figure 5), all exhibited highly significant differences both overall and by cultivar. Overall, total soluble solids exhibited similar values in 2021 and 2022 under the DI regime (21.58–22.03 °Brix), but in the SI regime, they were higher in 2022 (22.74 °Brix) compared to 2021 (22.20 °Brix). In red cultivars, total soluble solids reached maximum value (over 25.50 °Brix) in Syrah, whereas Moravia Agria barely reached 21 °Brix when grown under the DI regime. This could be because this cultivar exhibited a very high Ravaz index—both high average yield and low average vine growth—and, therefore, the grapes could not fully ripen, despite being one of the cultivars that was harvested later in both years (Table S1). Regarding white cultivars, the lowest values of total soluble solids were recorded in Airén and Azargón (DI regime) (below 19°Brix). Conversely, Blanca del Tollo and Riesling under the DI regime and Moscatel Serrano under the SI regime exhibited the highest values of total soluble solids (over 23 °Brix). Albillo Dorado stood out as the cultivar that reached the earliest ripeness in both years (August 4) (Table S1), even earlier than Chardonnay (August 12–13), which allowed its cycle to be the shortest among all cultivars (107–112 days).

As for total acidity levels, they were lower overall in 2022 than in 2021 (Figure 5), likely due to warmer conditions during the summer months (Figure 1), as reported by Poni *et al*. (2018). Regarding the water regime, total acidities were greater under the SI regime than the DI regime. Specifically, in 2021, total acidities averaged 5.32 and 5.87 g L^{-1} for the

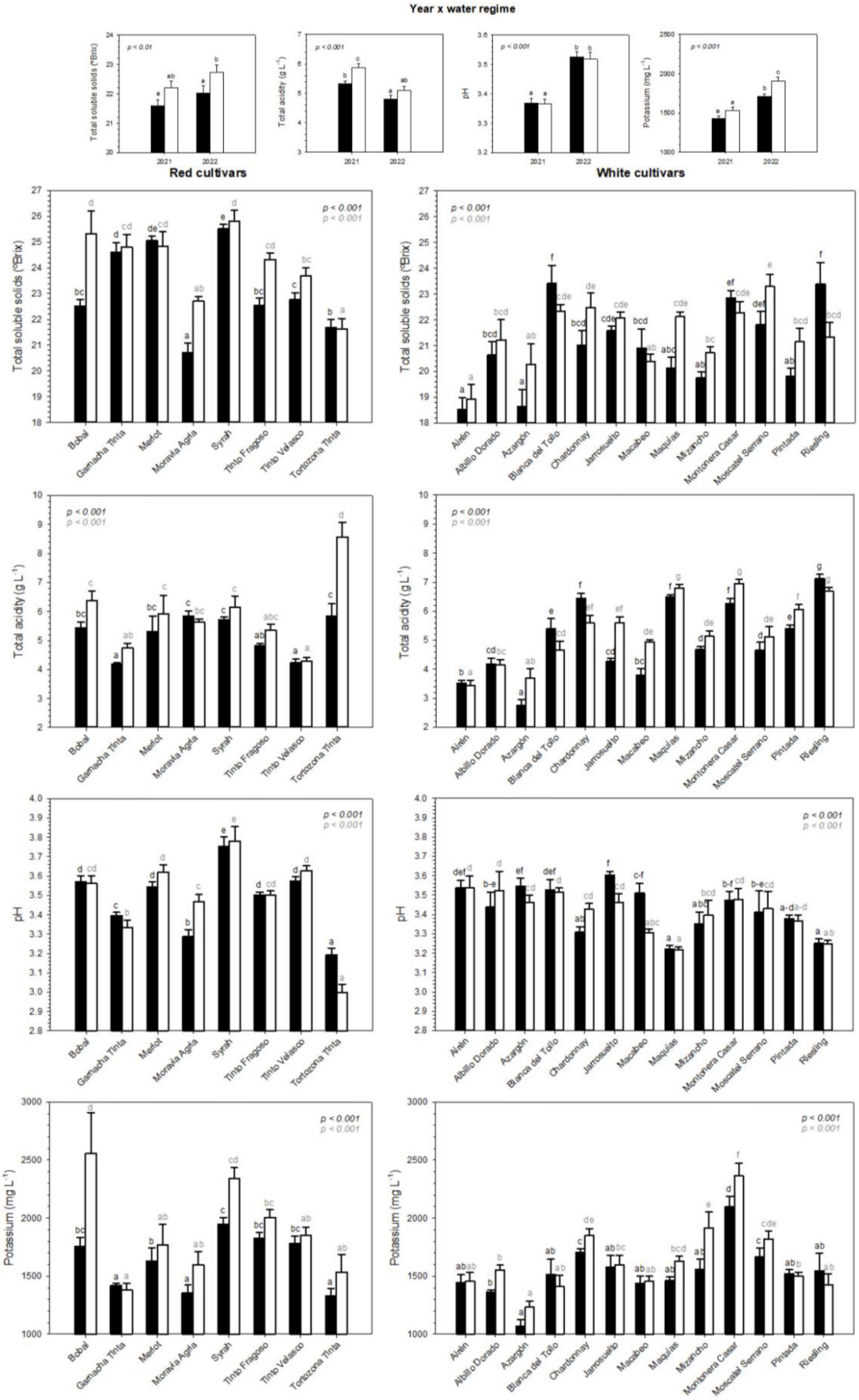

FIGURE 5. Must physicochemical parameters. Columns and error bars depict averages and standard error, respectively, of 10 samples (5 replicates each year) or 105 samples (year × water regime plots). The black and white columns are values from the DI (moderate water stress) and SI (severe water stress) regimes, respectively. Different letters indicate statistically significant differences among different cultivars or among the different year–water regime combinations (year × water regime plots) by Duncan's test.

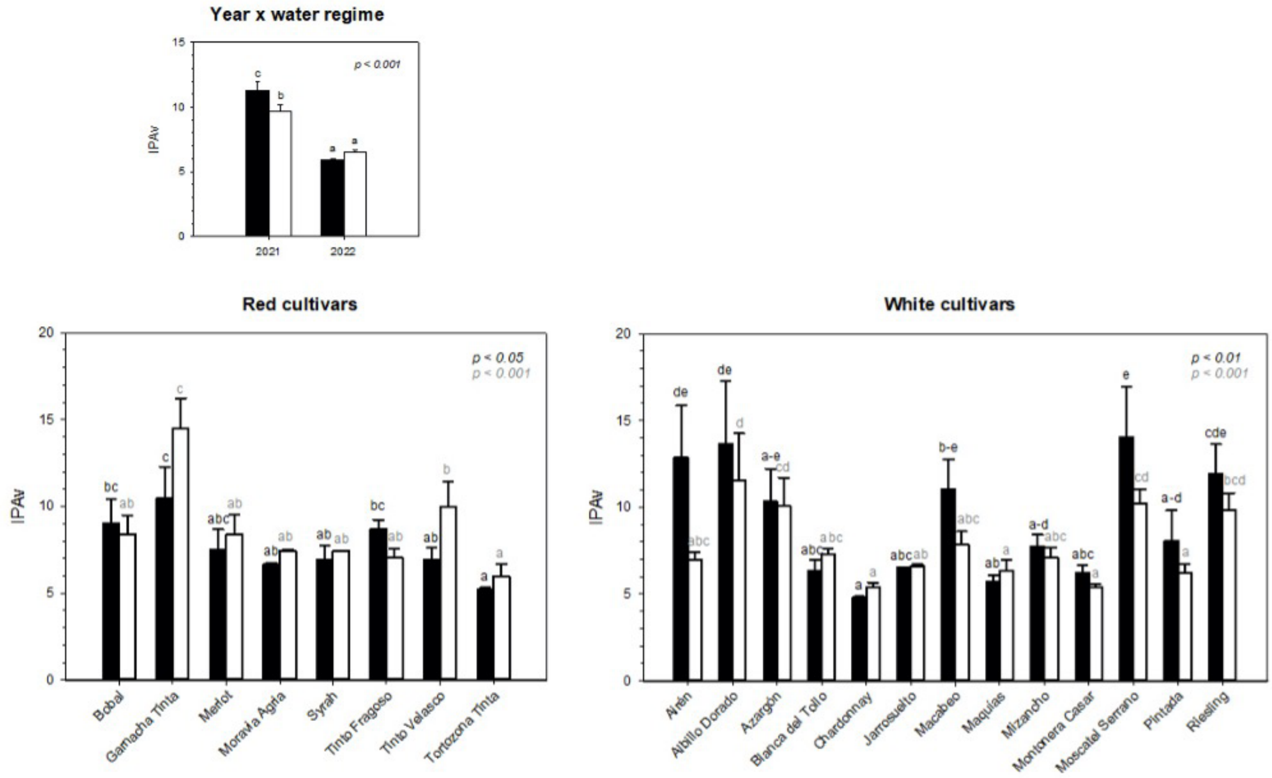

FIGURE 6. Varietal aroma potential index. Columns and error bars depict averages and standard error, respectively, of 4 samples (2 replicates each year) or 42 samples (year × water regime plots). The black and white columns are values from the DI (moderate water stress) and SI (severe water stress) regimes, respectively. Different letters indicate statistically significant differences among different cultivars or among the different year–water regime combinations (year × water regime plots) by Duncan's test.

DI and SI regimes, respectively. However, in 2022 they were 4.81 and 5.10 g L^{-1}, respectively. All red cultivars, when grown under the DI regime, exhibited total acidities below 6 g L^{-1}. Moravia Agria, Syrah, and Tortozona Tinta had the highest values (5.71–5.85 g L^{-1}), whereas others, such as Garnacha Tinta and Tinto Velasco, exhibited the lowest values (approximately 4.20 g L^{-1}). Under the SI regime, Tortozona Tinta stood out, by far, with the highest total acidity (8.57 g L^{-1}), being the cultivar whose acidity benefited most from drought conditions—an increase greater than 2.50 g L^{-1} compared to the DI regime—. By contrast, Tinto Velasco exhibited the lowest total acidity value (4.30 g L^{-1}). Total acidity values obtained in this study for the Bobal cultivar were similar to those obtained by Pérez-Álvarez *et al*. (2021) when grown under a DI regime and slightly higher when grown under severe drought conditions. These differences may be attributable to the rootstock, different soil and climate conditions, and vine management. Regarding white cultivars, Chardonnay (DI regime), Pintada (SI regime), Maquías, Montonera del Casar, and Riesling were remarkable, producing total acidities over 6 g L^{-1}. However, others, such as Airén and Azargón, exhibited total acidities below 4 g L^{-1}.

On the other hand, pH values in musts varied among years but not among water regimes (Figure 5), which is consistent with the findings reported by other authors who have found no significant effect of irrigation on must pH (Chaves *et al*., 2007; Intrigliolo *et al*., 2016). In 2021, the average pH values were approximately 3.37, whereas in 2022 they were higher, at approximately 3.52. In red cultivars, the maximum pH values, above 3.75, were recorded in Syrah. By contrast, Tortozona Tinta indicated the lowest pH values (3.00–3.19). In most white cultivars, pH values ranged from 3.40 to 3.60, whereas Maquías and Riesling had the lowest pH values (3.22–3.25). Chardonnay was the only cultivar that experienced a significant impairment to both pH and total acidity as a consequence of drought conditions (Table S2).

Finally, average potassium in musts was similar in both water regimes in 2021 (1,431–1,535 mg L^{-1}), whereas in 2022 it was higher in musts from the SI regime (1,908 mg L^{-1}) than in the DI regime (1,715 mg L^{-1}) (Figure 5). A particularly warmer summer (Figure 1), led to a higher accumulation of potassium in musts in 2022 compared to 2021, with a clear impact on pH increase, as reported by Rogiers *et al*. (2017). In red cultivars, potassium varied over a wide range when vines were grown under the SI regime (1,179 mg L^{-1}), but it was lower under the DI regime (615 mg L^{-1}). Bobal and Syrah stood out under the SI regime exhibiting 2,558 and 2,344 mg L^{-1}, respectively. By contrast, cultivars such as

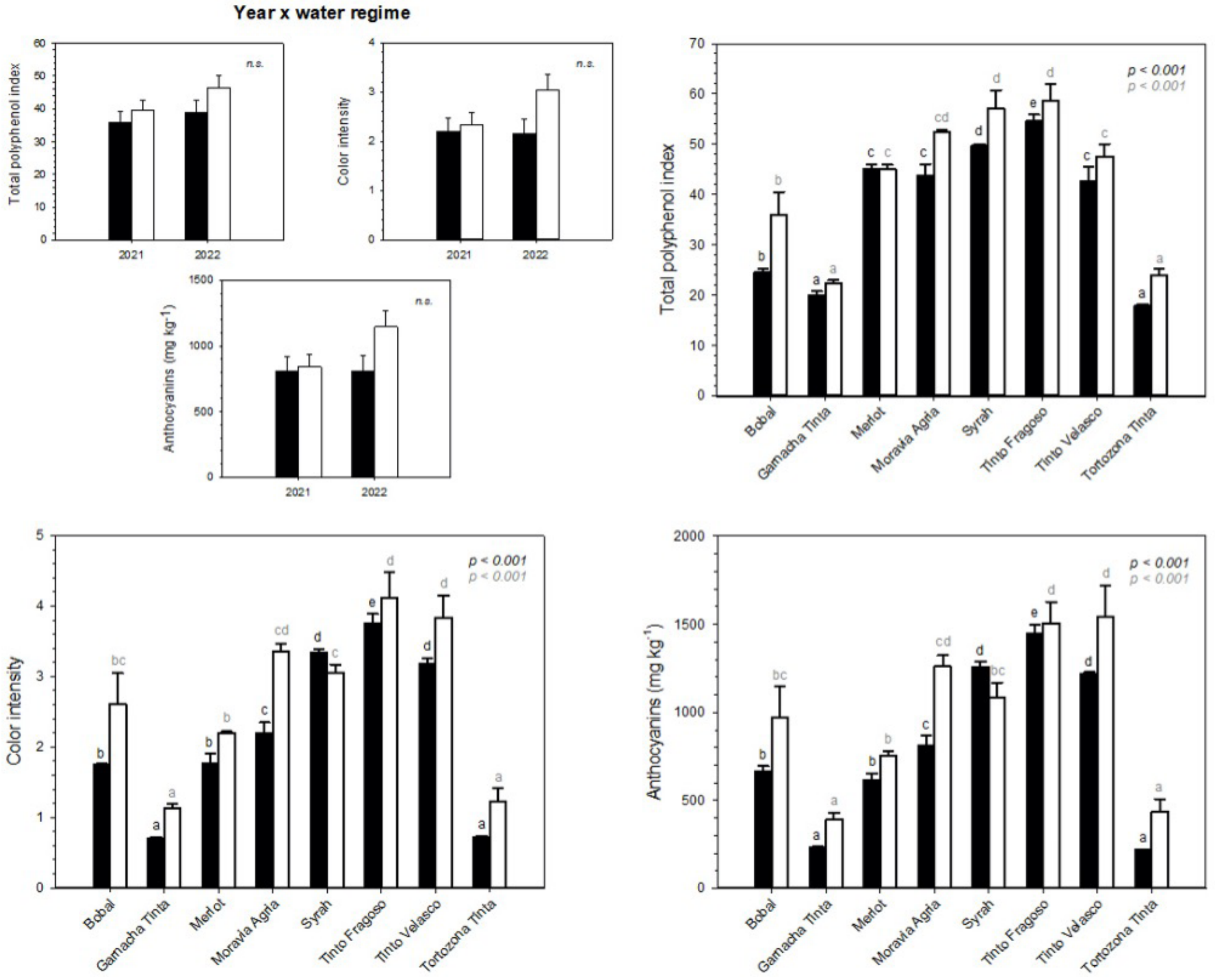

FIGURE 7. Grape colour parameters. Columns and error bars depict averages and standard error, respectively, of 4 samples (2 replicates each year) or 16 samples (year × water regime plots). The black and white columns are values from the DI (moderate water stress) and SI (severe water stress) regimes, respectively. Different letters indicate statistically significant differences among different cultivars or among the different year–water regime combinations (year × water regime plots) by Duncan's test. n.s. indicates no statistically significant differences.

Garnacha Tinta exhibited values below 1,500 mg L^{-1}. Among white cultivars, Montonera del Casar musts had the highest potassium concentrations (over 2,000 mg L^{-1}), whereas they were below 1,300 mg L^{-1} in cultivars such as Azargón. Jarrosuelto, Macabeo, and Tortozona Tinta stood out as the cultivars whose total acidity and pH values were significantly improved by drought conditions, without affecting total soluble solids and potassium concentration (Table S2). These qualities make them particularly interesting for growing under severe water stress conditions.

3. Grape quality

The method that provides the varietal aroma potential index (IPAv) is based on the analysis of glycosylated aroma precursors of grapes, musts, and wines. This method was developed by Salinas *et al*. (2012) and was adapted subsequently by Serrano de la Hoz *et al*. (2014). Overall, IPAv varied significantly among years and water regimes ($p < 0.001$; Figure 6), recording the highest average values in 2021 under the DI regime (11.30). The lowest IPAv values were recorded in 2022, which were similar in both water regimes (5.91–6.51). This reduction in IPAv is likely due to the warmer conditions during grape ripening in 2022 than in 2021 (Figure 1), which is consistent with results reported by Crespo *et al*. (2018). Among red cultivars, Garnacha Tinta was remarkable for recording the highest IPAv values (over 10), whereas Tortozona Tinta exhibited values below 6. As for white cultivars, Albillo Dorado, Azargón, and Moscatel Serrano stood out with values over 10. By contrast, cultivars such as Chardonnay recorded the lowest values (below 6). No cultivar exhibited significant differences between the IPAv values obtained in both water regimes (Table S2), so it was not possible to establish a behaviour pattern between water availability and the aromatic potential of grapes.

Regarding colour parameters in red cultivars, there were no significant differences among values obtained in both years for each water regime in any of the parameters analysed (Figure 7). However, when the values were considered by cultivar, highly significant differences were recorded in all cases ($p < 0.001$). Regarding the total polyphenol index (TPI), the lowest values were recorded in Garnacha Tinta and Tortozona Tinta in both the DI (below 20) and SI (below 24) regimes. By contrast, Syrah and Tinto Fragoso exhibited the highest TPI values (49.80–57.14). In terms of colour intensity (CI), Garnacha Tinta and Tortozona Tinta exhibited the lowest CI values, both under the DI (0.70–0.72) and SI (1.12–1.23) regimes. Conversely, Tinto Fragoso and Tinto Velasco (SI regime) exhibited the highest CI values (3.75–4.11). Anthocyanins indicated the same trend as CI; Garnacha Tinta and Tortozona Tinta recorded the lowest values (below 500 mg kg^{-1}), whereas Tinto Fragoso and Tinto Velasco (SI regime) stood out with concentrations above 1,400 mg kg^{-1}. All colour parameters analysed—TPI, CI, and anthocyanins—exhibited a positive response to drought in Tortozona Tinta and Moravia Agria, whose values increased significantly with respect to the DI regime (Table S2).

In this study, a strong correlation was obtained between colour intensity and anthocyanin concentration. The regression demonstrated a very high coefficient of determination ($R^2 = 0.98$) as well as a high level of significance ($p < 0.001$), meaning that the equation of the line ($y = 393.85\ x - 61.25$) would allow for the precise establishment of the anthocyanin concentration from colour intensity, without the need to apply the methodology of Ribéreau-Gayon and Stronestreet (1965).

4. Carbon isotope ratio

The overall carbon isotope ratio ($\delta^{13}C$) varied over a wide range (Figure 8), extending from –25.99 to –20.78 ‰, allowing for differentiation of the water status sustained by vines of each water regime. In both 2021 and 2022, the central tendency (average and median) of the $\delta^{13}C$ data of DI regime vines remained between –25 and –24 ‰ (indicating moderate stress; Santesteban *et al*. (2015)). However, in 2021, the highest data frequency (violin width) of the DI regime was above –24 ‰ (indicating severe stress; Santesteban *et al*. (2015)). Regarding the SI regime, although the vines maintained severe stress (above –24 ‰) in both years, in 2022 they were more stressed than in 2021 (averaging –22.61 and –22.82 ‰, respectively).

Most red cultivars indicated average $\delta^{13}C$ values between –25 and –24 ‰ when grown under the DI regime, which means moderate water stress (Figure 8). However, Bobal and Tinto Fragoso exhibited average values above –24 ‰ and, therefore, severe stress. As for the SI regime, the interquartile range (boxes) for the $\delta^{13}C$ data of all red cultivars was in the severe stress range (over –24 ‰). Merlot recorded the lowest levels of water stress when grown under the SI regime ($\delta^{13}C$ average of –23.26 ‰) and Tinto Fragoso the highest under the DI regime ($\delta^{13}C$ average of –23.57 ‰). Moravia Agria presented an opposite case: It was the most-stressed cultivar under the SI regime ($\delta^{13}C$ average of –22.23 ‰) but the least-stressed under the DI regime ($\delta^{13}C$ average of –25.00 ‰).

Only six of 13 white cultivars under the DI regime had average $\delta^{13}C$ values in the moderate stress range (Figure 9), whereas the remaining cultivars were located in the severe stress range. Macabeo exhibited the lowest water stress levels (–24.94 ‰, on average), whereas Montonera del Casar and Pintada were the most-stressed cultivars (–23.51 and –23.52 ‰, on average, respectively). As for the SI regime, all white cultivars had their interquartile range in the severe stress range, but differences among them were noted. Airén, Chardonnay, and Riesling (–23.38 to –23.27 ‰, on average) exhibited less severe stress than Mizancho (–21.78 ‰, on average). In general, the $\delta^{13}C$ data from the DI regime indicated less dispersion than those from the SI regime.

For a given cultivar, large differences between $\delta^{13}C$ values obtained in the DI and SI regimes indicate significant variations in the water status of vines according to water availability; therefore, this denotes an anisohydric behaviour. This is the case for cultivars such as Blanca del Tollo, Macabeo, and Moravia Agria, whose ranges greater than 2 ‰ between average values of the DI and SI regimes indicated a behaviour close to anisohydry. These cultivars obtained a high benefit from irrigation since they were able to adjust their water status depending on the water availability. These results agree with the findings of Serrano *et al*. (2024) for these same cultivars based on stomatal and water potential regulation.

5. Classification of cultivars according to their behaviour based on multiple variables

Four principal component analyses (PCAs) were performed (Figure 10). Considering all parameters measured in this study and with the help of cluster analysis, groupings of cultivars were identified according to their response based on these parameters. PCAs explained variances ranging from 59.03 (white cultivars, SI regime) to 67.71 % (red cultivars, DI regime). Regarding red cultivars, under the DI regime, three groupings were identified. On the one hand, Bobal, Garnacha Tinta, and Tortozona Tinta were positioned opposite to the axes of colour parameters, pH, and potassium; whereas Merlot, Syrah, Tinto Fragoso, and Tinto Velasco were positioned close to these axes. Moravia Agria was isolated toward the yield, Ravaz index, and total acidity axes. When they were grown under the SI regime, four groupings were identified. Syrah, Tinto Fragoso, and Tinto Velasco were still positioned together, close to the axes of colour parameters, pH, and potassium, in addition to the axes of pruning weight and total soluble solids. By contrast, Bobal, Garnacha Tinta, and Tortozona Tinta were not positioned together: Garnacha Tinta was seen along the yield, Ravaz index, and IPAv axes; whereas Tortozona Tinta was positioned toward the total acidity axis; and Bobal was grouped together with Syrah, Tinto Fragoso, and Tinto Velasco. Merlot and Moravia Agria adopted a position close to centrality, near the Ravaz index and total acidity axes.

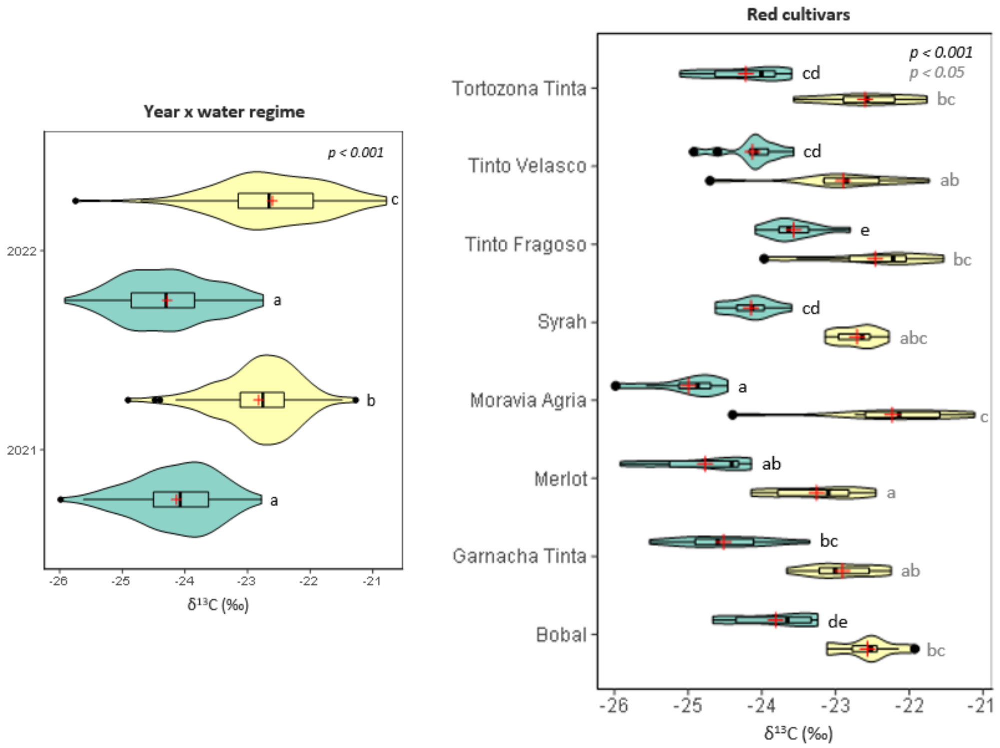

FIGURE 8. Violin plots of must δ^{13}C values considering all cultivars (red and white) together and red cultivars separately. Violins depict values of 10 samples (5 replicates each year) or 105 samples (year × water regime plot). Blue and yellow violins depict values from the DI (moderate water stress) and SI (severe water stress) regimes, respectively. Different letters indicate statistically significant differences among different cultivars or among the different year–water regime combinations (year × water regime plot) by Duncan's test.

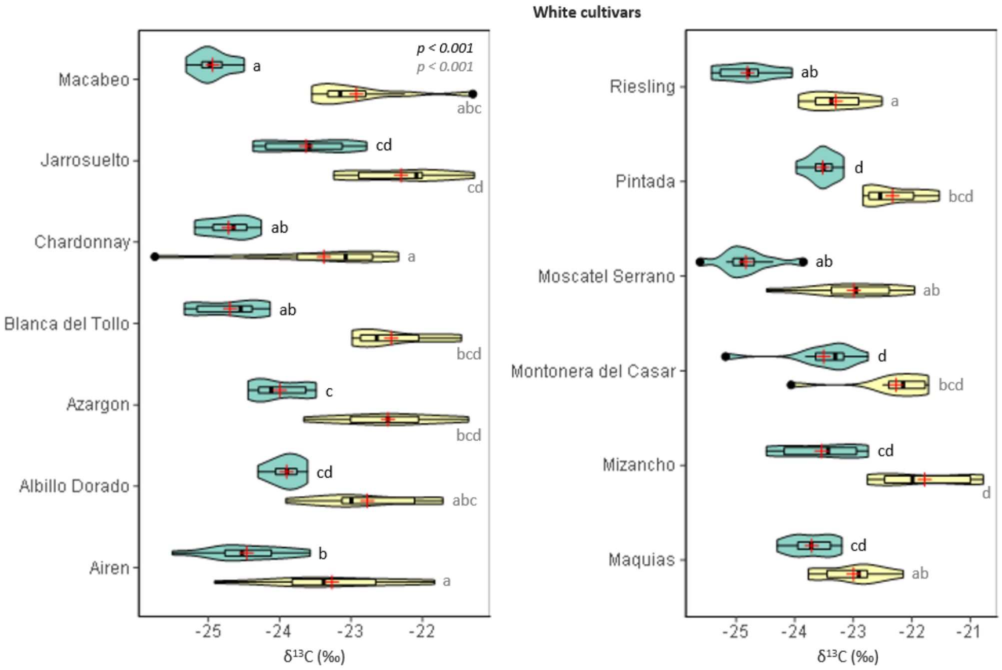

FIGURE 9. Violin plots of must δ13C values of white cultivars separately. Violins depict values of 10 samples (5 replicates each year). Blue and yellow violins depict values from the DI (moderate water stress) and SI (severe water stress) regimes, respectively. Different letters indicate statistically significant differences among the different cultivars by Duncan's test.

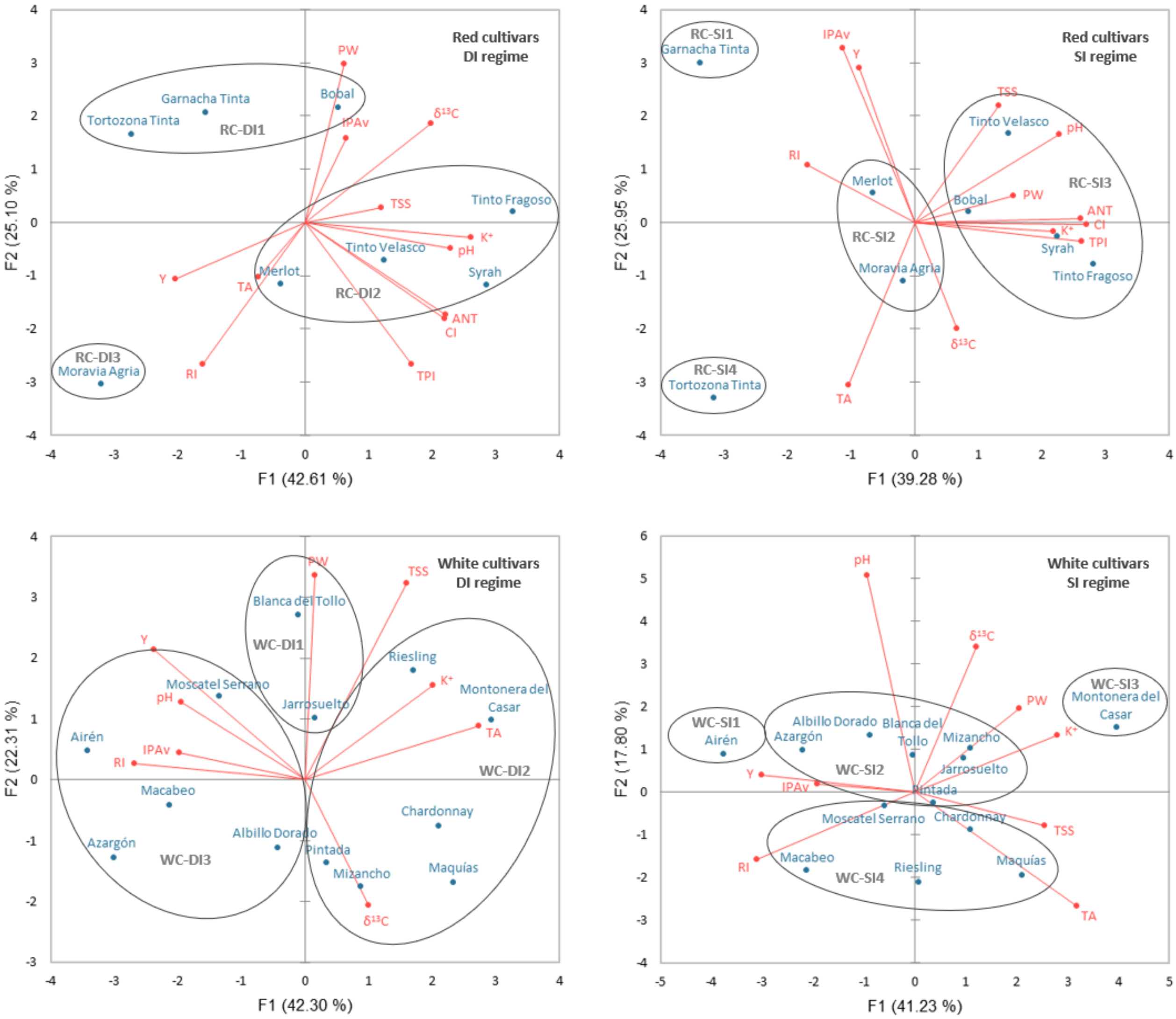

FIGURE 10. Principal components analyses (PCAs). Notes: DI: moderate water stress; SI: severe water stress; Y: yield; PW: pruning weight; RI: Ravaz index; TSS: total soluble solids; TA: total acidity; pH: pH; K⁺: potassium; δ^{13}C: carbon isotope ratio; IPAv: varietal aroma potential index; TPI: total polyphenol index; CI: colour intensity; ANT: anthocyanins.

As for white cultivars, three groupings were differentiated under the DI regime (Figure 10). First, Blanca del Tollo and Jarrosuelto were located toward the pruning weight axis, and Airén, Albillo Dorado, Azargón, Macabeo, and Moscatel Serrano were clustered toward the yield, Ravaz index, pH, and IPAv axes. Conversely, Chardonnay, Maquías, Montonera del Casar, Mizancho, Pintada, and Riesling were clustered toward the potassium, total acidity, and δ^{13}C axes. Under the SI regime, four groupings of cultivars were differentiated. Airén was isolated to the yield and IPAv axes, whereas Montonera del Casar was isolated to the pruning weight and potassium axes. At the bottom of the plot, Chardonnay, Macabeo, Maquías, Moscatel Serrano, and Riesling were grouped near the total acidity and Ravaz index axes. The remaining cultivars were grouped in the upper-central part of the PCA. As can be seen, Maquías was grouped with Chardonnay and Riesling in both water regimes. The similarities of these three cultivars extend beyond the results obtained in this work: Previous studies have reported that their grapes also exhibited a similar phenolic profile (Parra *et al.*, 2023).

To facilitate the interpretation of the traits of each group identified in Figure 10, a heatmap was compiled with the average values of each variable for each group (Table 2). In this heatmap, groups were identified with the same alphanumeric code that appeared within groups in Figure 10. When red cultivars were grown under the DI regime, those integrated into the RC-DI1 group exhibited good response in terms of vigour and aromatic potential and moderate response in the case of yield and must quality; however, their colour potential was low for producing red wines. The RC-DI2 group demonstrated a good response in terms of colour parameters but poor in terms of yield, pH, and potassium. The RC-DI3 group, composed only of Moravia Agria,

TABLE 2. Heatmap with the average values of each variable for each group identified in Figure 10.

Group	Y	PW	RI	TSS	TA	pH	K⁺	δ¹³C	IPAv	TPI	CI	ANT
RC-DI1	2.63	0.52	5.48	22.94	5.18	3.39	1,504.10	-24.18	8.23	20.84	1.06	370.57
RC-DI2	2.12	0.36	6.83	23.96	5.02	3.59	1,796.66	-24.15	7.50	48.04	3.01	1,135.26
RC-DI3	3.90	0.21	20.35	20.72	5.84	3.29	1,352.80	-25.00	6.64	43.82	2.20	810.47
RC-SI1	2.45	0.24	11.49	24.80	4.73	3.34	1,379.30	-22.91	14.19	22.34	1.12	392.31
RC-SI2	1.34	0.12	11.25	23.77	5.77	3.54	1,684.68	-22.74	7.91	48.75	2.78	1,007.58
RC-SI3	1.61	0.34	4.69	24.78	5.55	3.62	2,189.77	-22.66	8.20	49.80	3.40	1,276.46
RC-SI4	1.23	0.23	5.69	21.63	8.57	3.00	1,533.90	-22.60	5.96	23.99	1.23	434.38
WC-DI1	4.03	0.74	6.14	22.51	4.83	3.56	1,547.71	-24.16	6.44			
WC-DI2	1.80	0.44	4.67	21.16	6.07	3.33	1,649.42	-23.97	7.41			
WC-DI3	4.00	0.42	10.23	20.11	3.78	3.49	1,396.76	-24.43	12.39			
WC-SI1	3.67	0.35	10.57	18.94	3.44	3.54	1,458.80	-23.27	6.99			
WC-SI2	1.55	0.32	4.69	21.30	4.88	3.45	1,535.46	-22.34	8.14			
WC-SI3	0.97	0.62	1.86	22.27	6.95	3.48	2,364.22	-22.41	5.40			
WC-SI4	1.62	0.29	6.69	21.93	5.83	3.33	1,636.25	-23.12	7.91			

Notes: Y: yield (kg vine^{-1}); PW: pruning weight (kg vine^{-1}); RI: Ravaz index; TSS: total soluble solids (°Brix); TA: total acidity (g L^{-1}); pH: pH; K$^+$: potassium (mg L^{-1}); δ^{13}C: carbon isotope ratio (‰); IPAv: varietal aroma potential index; TPI: total polyphenol index; CI: colour intensity; ANT: anthocyanins (mg kg^{-1}). The colour scale goes from red (more negative values) to white (more positive values).

indicated a good response in terms of yield, must quality, and water stress level but a negative reaction in terms of components related to vigour and sugar accumulation. Among those cultivars grown under the SI regime, the RC-SI2 group demonstrated the most balanced response in the parameters considered except for yield and vigour, where the response was negative. On the other hand, the RC-SI3 group was characterised mainly by high values for colour parameters but a negative response for pH and potassium.

As for white cultivars grown under DI conditions (Table 2), the WC-DI1 group exhibited high yield and vigour, but its response was moderate to low in terms of quality. By contrast, cultivars in the WC-DI2 group exhibited low yields but good quality parameters. Those integrated into the WC-DI3 group were characterised mainly by high yields and aromatic potential but very low total acidities. Among white cultivars grown under the SI regime, the ones indicating a better balance among most parameters considered were those integrated into the WC-SI2 and WC-SI4 groups, although there were differences among them. While it demonstrated lower vigour, the WC-SI4 group had greater must quality due to its high acidity and low pH values. Conversely, the WC-SI1 group, composed only of Airén, exhibited high yield and a high Ravaz index as well as low level of water stress but low must quality due to its low sugar concentration and total acidity as well as high pH. Finally, the WC-SI3 group, formed only by Montonera del Casar, was characterised by the lowest yield but the highest value of pruning weight, which resulted in an imbalance between production and vigour—a low Ravaz index—. However, although its total acidity was high, the concentration of potassium in its musts was also high, and its aromatic potential was low.

CONCLUSIONS

This study has allowed assessing the influence of two water stress levels on agronomic and quality traits of a large number of red and white grapevine cultivars, for most of which there are no related previous studies. Depending on the water regime severity the cultivars that stood out were different, but in general, among the reds, cultivars such as Tinto Fragoso and Tinto Velasco stood out for exhibiting qualities similar to Syrah, being particularly characterised by high values regarding colour parameters. Among the white ones, Maquías stood out for exhibiting similar traits to those of international cultivars such as Chardonnay and Riesling, whose main characteristic was their high total acidity and low pH values. Knowing the response of yield and grape quality in different grapevine cultivars grown under water deficit conditions is essential in selecting the most suitable ones and improving the irrigation water management of each of them. This would make it easier for viticulture to remain sustainable in some areas that are increasingly threatened by the effects of climate change, depending on their water resources and edaphoclimatic conditions.

ACKNOWLEDGEMENTS

A. Sergio Serrano is grateful for her predoctoral contract granted by the University of Castilla-La Mancha (UCLM) and co-financed by the European Social Fund under the

Operational Programme 2014–2020 of Castilla-La Mancha. The authors acknowledge the funding received from the Next Generation Scientific Infrastructure Funds for the acquisition of the IRMS equipment (Project EQC2021-007049-P) and the funding from the European Regional Development Fund under the Operational Programme 2021–2027 of Castilla-La Mancha through the project "Development of strategies for the assessment of the resilience of woody crops and varieties in the face of climate change".

REFERENCES

Alatzas, A., Theocharis, S., Miliordos, D. E., Leontaridou, K., Kanellis, A. K., Kotseridis, Y., Hatzopoulos, P., & Koundouras, S. (2021). The Effect of Water Deficit on Two Greek *Vitis vinifera* L. Cultivars: Physiology, Grape Composition and Gene Expression during Berry Development. *Plants 2021, 10*(9), 1947. https://doi.org/10.3390/PLANTS10091947

Allen, R. G., Pereira, L. S., Raes, D., & Smith, M. (2006). Evapotranspiración del cultivo: Guías para la determinación de los requerimientos de agua de los cultivos. *Fao*, *298*.

Antolín, M. C., Salinas, E., Fernández, A., Gogorcena, Y., Pascual, I., Irigoyen, J. J., & Goicoechea, N. (2022). Prospecting the Resilience of Several Spanish Ancient Varieties of Red Grape under Climate Change Scenarios. *Plants*, *11*(21), 1–21. https://doi.org/10.3390/plants11212929

Bchir, A., Escalona, J. M., Gallé, A., Hernández-Montes, E., Tortosa, I., Braham, M., & Medrano, H. (2016). Carbon isotope discrimination ($\delta^{13}C$) as an indicator of vine water status and water use efficiency (WUE): Looking for the most representative sample and sampling time. *Agricultural Water Management*, *167*, 11–20. https://doi.org/10.1016/J.AGWAT.2015.12.018

Bravdo, B., Hepner, Y., Loinger, C., Cohen, S., & Tabacman, H. (1985). Effect of Crop Level and Crop Load on Growth, Yield, Must and Wine Composition, and Quality of Cabernet Sauvignon. *American Journal of Enology and Viticulture*, *36*(2).

Brillante, L., Martínez-Lüscher, J., Yu, R., & Kurtural, S. K. (2020). Carbon Isotope Discrimination ($\delta^{13}C$) of Grape Musts Is a Reliable Tool for Zoning and the Physiological Ground-Truthing of Sensor Maps in Precision Viticulture. *Frontiers in Environmental Science*, *8*(September), 1–17. https://doi.org/10.3389/fenvs.2020.561477

Chacón-Vozmediano, J. L., Martínez-Gascueña, J., García-Navarro, F. J., & Jiménez-Ballesta, R. (2020). Effects of water stress on vegetative growth and 'Merlot' grapevine yield in a semi-arid Mediterranean climate. *Horticulturae*, *6*(4), 1–18. https://doi.org/10.3390/horticulturae6040095

Chacón-Vozmediano, J. L., Martínez-Gascueña, J., García-Romero, E., Gómez-Alonso, S., García-Navarro, F. J., & Jiménez-Ballesta, R. (2021). Effects of Water Stress on the Phenolic Compounds of 'Merlot' Grapes in a Semi-Arid Mediterranean Climate. *Horticulturae 2021,* 7, 161. https://doi.org/10.3390/horticulturae7070161

Chaves, M. M., Santos, T. P., Souza, C. R., Ortuño, M. F., Rodrigues, M. L., Lopes, C. M., Maroco, J. P., & Pereira, J. S. (2007). Deficit irrigation in grapevine improves water-use efficiency while controlling vigour and production quality. *Annals of Applied Biology*, *150*(2), 237–252. https://doi.org/10.1111/J.1744-7348.2006.00123.X

Chaves, M. M., Zarrouk, O., Francisco, R., Costa, J. M., Santos, T., Regalado, A. P., Rodrigues, M. L., & Lopes, C. M. (2010). Grapevine under deficit irrigation: hints from physiological and molecular data. In *Annals of botany*, 105(5), 661–676. https://doi.org/10.1093/aob/mcq030

Crespo, J., Rigou, P., Romero, V., García, M., Arroyo, T., & Cabellos, J. M. (2018). Effect of seasonal climate fluctuations on the evolution of glycoconjugates during the ripening period of grapevine cv. Muscat à petits grains blancs berries. *Journal of the Science of Food and Agriculture*, *98*(5), 1803–1812. https://doi.org/10.1002/jsfa.8656

Farquhar, G., Ehleringer, J., & Hubick, K. (1989). Carbon isotope discrimination and photosynthesis. *Annual Review of Plant Biology*, *40*, 503–537. https://www.academia.edu/download/42237597/Carbon_isotope_discrimination_and_photos20160206-11499-1s8u0ia.pdf

Florez-Sarasa, I., Clemente-Moreno, M. J., Cifre, J., Capo, M., Llompart, M. Q., Fernie, A. R., & Bota, J. (2020). Differences in Metabolic and Physiological Responses between Local and Widespread Grapevine Cultivars under Water Deficit Stress. *Agronomy 2020,* 10(7), 1052. https://doi.org/10.3390/agronomy10071052

Gaussen, H. and Bagnouls, F. (1953). Dry Season and Xerothermic Index. *Bulletin de La Société d'Histoire Naturelle de Toulouse*, *88*, 193–240.

Gisbert, C., Soler, J. X., Fos, M., Intrigliolo, D. S., Yuste, A., Picó, B., Torrent, D., & Peiró, R. (2022). Characterization of Local Mediterranean Grapevine Varieties for Their Resilience to Semi-Arid Conditions under a Rain-Fed Regime. *Agronomy*, *12*(9). https://doi.org/10.3390/agronomy12092234

Glories, Y. (1984). La couleur des vins rouges. *Connaiss. Vigne Vin.*, *18*, 253–271.

Huglin, M. (1978). Nouveau mode d'évaluation des possibilités héliothermiques d'un milieu viticole. *Académie Agric. Fr.*, *64*, 1117–1126.

OIV (2024). *Compendium of International Methods of Wine and Must Analysis*. Retrieved March 10, 2024, from https://www.oiv.int/standards/compendium-of-international-methods-of-wine-and-must-analysis

Intrigliolo, D. S., Lizama, V., García-Esparza, M. J., Abrisqueta, I., & Álvarez, I. (2016). Effects of post-veraison irrigation regime on Cabernet Sauvignon grapevines in Valencia, Spain: Yield and grape composition. *Agricultural Water Management*, *170*, 110–119. https://doi.org/10.1016/j.agwat.2015.10.020

Junquera, P., Lissarrague, J. R., Jiménez, L., Linares, R., & Baeza, P. (2012). Long-term effects of different irrigation strategies on yield components, vine vigour, and grape composition in cv. Cabernet-Sauvignon (*Vitis vinifera* L.). *Irrigation Science*, *30*(5), 351–361. https://doi.org/10.1007/s00271-012-0348-y

Korkutal, I., Bahar, E., & Carbonneau, A. (2019). Effects of early water stress on grapevine (*Vitis vinifera* L.) growing in cv. Syrah. *Researchgate.Net*. https://doi.org/10.15666/aeer/1701_463472

Lorenz, D. H., Eichhorn, K. W., Bleiholder, H., Klose, R., Meier, U., & Weber, E. (1995). Growth Stages of the Grapevine: Phenological growth stages of the grapevine (*Vitis vinifera* L. ssp. vinifera)—Codes and descriptions according to the extended BBCH scale†. *Australian Journal of Grape and Wine Research*, *1*(2), 100–103. https://doi.org/10.1111/J.1755-0238.1995.TB00085.X

Keller, M., Romero, P., Gohil, H., Smithyman, R. P., Riley, W. R., Casassa, L. F., & Harbertson, J. (2016). Deficit Irrigation Alters Grapevine Growth, Physiology, and Fruit Microclimate. *American Journal of Enology and Viticulture*, *67*, 426–435. https://doi.org/10.5344/ajev.2016.16032

Mateo, M. A., Ferrio, J. P., & Araus, J. L. (2004). Isótopos estables en fisiología vegetal. In *La ecofisiología vegetal, una ciencia de síntesis*, 113–160.

Mirás-Avalos, J. M., & Intrigliolo, D. S. (2017). Grape composition under abiotic constrains: Water stress and salinity. *Frontiers in Plant Science*, *8*, 851. https://doi.org/10.3389/FPLS.2017.00851/BIBTEX

Munitz, S., Netzer, Y., & Schwartz, A. (2017). Sustained and regulated deficit irrigation of field-grown Merlot grapevines. *Australian Journal of Grape and Wine Research*, *23*(1), 87–94. https://doi.org/10.1111/ajgw.12241

Muñoz-Organero, G., Espinosa, F. E., Cabello, F., Zamorano, J. P., Urbanos, M. A., Puertas, B., Lara, M., Domingo, C., Puig-Pujol, A., Valdés, M. E., Moreno, D., Diaz-Losada, E., Martínez, M. C., Santiago, J. L., Cibriain, J. F., Raboso, E., & Fernández-Pastor, M. (2022). Phenological Study of 53 Spanish Minority Grape Varieties to Search for Adaptation of Vitiviniculture to Climate Change Conditions. *Horticulturae*, *8*(11). https://doi.org/10.3390/horticulturae8110984

Parra, A. S. S., Cebrián-Tarancón, C., Gascueña, J. M., Vozmediano, J. L. C., Zapata, M. D. C., & Alonso, G. L. (2023). Effect of two water deficit regimes on phenolic composition of 15 recovered grapevine varieties in Castilla-La Mancha region (Spain): A comparison with national and international varieties. *BIO Web of Conferences*, *56*, 01005. https://doi.org/10.1051/bioconf/20235601005

Pérez-Álvarez, E. P., Intrigliolo Molina, D. S., Vivaldi, G. A., García-Esparza, M. J., Lizama, V., & Álvarez, I. (2021). Effects of the irrigation regimes on grapevine cv. Bobal in a Mediterranean climate: I. Water relations, vine performance and grape composition. *Agricultural Water Management*, *248*, 106772. https://doi.org/10.1016/J.AGWAT.2021.106772

Poni, S., Gatti, M., Palliotti, A., Dai, Z., Duchêne, E., Truong, T. T., Ferrara, G., Matarrese, A. M. S., Gallotta, A., Bellincontro, A., Mencarelli, F., & Tombesi, S. (2018). Grapevine quality: A multiple choice issue. *Scientia Horticulturae*, *234*(May 2017), 445–462. https://doi.org/10.1016/j.scienta.2017.12.035

Reynolds, A. G. (1989). 'Riesling' Grapes Respond to Cluster Thinning and Shoot Density Manipulation. *Journal of the American Society for Horticultural Science*, *114*(3), 364–368. https://doi.org/10.21273/JASHS.114.3.364

Ribéreau-Gayon, J., Stronestreet, E. (1965). Le dosage des anthocyanes dans le vin rouge. *Bull. Soc. Chim.*, *9*, 2649–2652.

Ribéreau-Gayon, J.; Peynaud, E.; Sudraud, P.; Ribéreau-Gayon, P. (1982). *Traité d'Oenologie-Sciences et Techniques du vin, Tome I: Analyse et Contrôle Des Vins*. Dunod.

Rogiers, S. Y., Coetzee, Z. A., Walker, R. R., Deloire, A., & Tyerman, S. D. (2017). Potassium in the grape (*Vitis vinifera* L.) berry: Transport and function. *Frontiers in Plant Science*, *8*, 286884. https://doi.org/10.3389/FPLS.2017.01629/BIBTEX

Salinas, M. R., De La Hoz, K. S., Zalacain, A., Lara, J. F., & Garde-Cerdán, T. (2012). Analysis of red grape glycosidic aroma precursors by glycosyl glucose quantification. *Talanta*, *89*, 396–400. https://doi.org/10.1016/j.talanta.2011.12.050

Santesteban, L. G., Miranda, C., Barbarin, I., & Royo, J. B. (2015). Application of the measurement of the natural abundance of stable isotopes in viticulture: a review. *Australian Journal of Grape and Wine Research*, *21*(2), 157–167. https://doi.org/10.1111/ajgw.12124

Serrano, A. S., Martínez-Gascueña, J., & Chacón-Vozmediano, J. L. (2024). Variability in water use behavior during drought of different grapevine varieties: Assessment of their regulation of water status and stomatal control. *Agricultural Water Management*, *291*, 108642. https://doi.org/10.1016/j.agwat.2023.108642

Serrano, A. Sergio, Martínez-Gascueña, J., Alonso, G. L., Cebrián-Tarancón, C., Carmona, M. D., Mena Morales, A., & Chacón-Vozmediano, J. L. (2023). Variability in the Agronomic Behavior of 12 White Grapevine Varieties Grown under Severe Water Stress Conditions in the La Mancha Wine Region. *Horticulturae*, *9*(2). https://doi.org/10.3390/horticulturae9020243

Serrano, A Sergio, Martínez-Gascueña, J., Alonso, G. L., Cebrián-Tarancón, C., Carmona, M. D., Mena, A., & Chacón-Vozmediano, J. L. (2022). Agronomic Response of 13 Spanish Red Grapevine (*Vitis vinifera* L.) Cultivars under Drought Conditions in a Semi-Arid Mediterranean Climate. *Agronomy*, *12*(10). https://doi.org/10.3390/agronomy12102399

Serrano de la Hoz, K., Carmona, M., Zalacain, A., Alonso, G. L., & Salinas, M. R. (2014, November). The varietal aroma potential index (IPAv): A tool to evaluate the quality of grapes and wines, white and red. In Proceedings of the 37th World Congress of Vine and Wine, Mendoza, Argentina (pp. 9-14).

Smart, R. E., Dick, J. K., Gravett, I. M., & Fisher, B. M. (1990). Canopy Management to Improve Grape Yield and Wine Quality - Principles and Practices. *South African Journal of Enology and Viticulture*, *11*(1), 3–17. https://doi.org/10.21548/11-1-2232

van Leeuwen, C., Destrac-Irvine, A., Dubernet, M., Duchêne, E., Gowdy, M., Marguerit, E., Pieri, P., Parker, A., De Rességuier, L., & Ollat, N. (2019). An Update on the Impact of Climate Change in Viticulture and Potential Adaptations. *Agronomy 2019, 9*(9), 514. https://doi.org/10.3390/AGRONOMY9090514

Williams, L. E., Grimes, D. W., & Phene, C. J. (2010). The effects of applied water at various fractions of measured evapotranspiration on reproductive growth and water productivity of Thompson Seedless grapevines. *Irrigation Science*, *28*(3), 233–243. https://doi.org/10.1007/S00271-009-0173-0/FIGURES/8

Zarrouk, O., Costa, J. M., Francisco, R., Lopes, C., & Chaves, M. M. (2015). Drought and water management in Mediterranean vineyards. In *Grapevine in a Changing Environment*, 38–67. https://doi.org/10.1002/9781118735985.ch3

Zufferey, V., Verdenal, T., Dienes, A., Belcher, S., Lorenzini, F., Koestel, C., Blackford, M., Bourdin, G., Gindro, K., Spangenberg, J. E., Rösti, J., Viret, O., Carlen, C., & Spring, J. L. (2020). The influence of vine water regime on the leaf gas exchange, berry composition and wine quality of Arvine grapes in Switzerland. *Oeno One*, *54*(3), 553–568. https://doi.org/10.20870/oeno-one.2020.54.3.3106

Zufferey, V., Verdenal, T., Dienes, A., Belcher, S., Lorenzini, F., Koestel, C., Rösti, J., Gindro, K., Spangenberg, J. E., Viret, O., & Spring, J. L. (2018). The impact of plant water status on the gas exchange, berry composition and wine quality of Chasselas grapes in Switzerland. *OENO One*, *52*(4). https://doi.org/10.20870/OENO-ONE.2018.52.4.2181.