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Utilización del sistema de cordón vertical para mejorar el equilibrio fuente-sumidero y el aroma del vino en condiciones de escasez de agua en Maturana Blanca

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Trabajo de Fin de Máster

Utilización del sistema de cordón vertical para mejorar el equilibrio fuente-sumidero y el aroma del vino en condiciones de escasez de agua en Maturana Blanca

Utilization of vertical cordon system to improve source-sink balance and wine aroma under water shortage conditions of Maturana Blanca

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RESUMEN

En cultivares de vid de racimos pequeños, las condiciones de éxito de una forma de conducción libre para garantizar un nivel de rendimiento y calidad suficiente podrían pasar por el establecimiento de un cordón vertical permanente para mejorar el equilibrio de la vid y retener un mayor número de yemas sin crear una masa vegetal demasiado densa. En este caso, es importante cuantificar las relaciones fuente-sumidero en términos de respuesta general de la vid a la escasez de agua. Se examinó la influencia de dos tipos de poda corta (vaso (HT) vs. cordón vertical (VCT)) en condiciones de campo en el cultivar local Maturana Blanca con el fin de lograr un rendimiento óptimo bajo dos regímenes de riego (sin riego y con riego al 30% de la ET0). Para ello se midió el desarrollo vegetativo, el rendimiento, la composición del fruto y los compuestos volátiles del vino. El sistema VCT ha demostrado aumentar el rendimiento hasta 1,8 veces en comparación con el sistema HT, independientemente del régimen de riego. Aunque se observaron claras diferencias en las relaciones fuente-sumidero entre los dos sistemas de conducción, estas diferencias no afectaron a la maduración de las uvas ni a su calidad. Sin embargo, la reducción del tamaño de las bayas y la mayor exposición de los racimos en las vides VCT dieron lugar a una mayor concentración de compuestos aromáticos en los vinos obtenidos en comparación con los vinos de las vides HT. Este estudio indica la mejora de la relación fuente-sumidero del cv. Maturana Blanca a través de un cambio en el sistema de conducción, que ayuda a aumentar la interceptación de la luz, lo que conduce a un mayor potencial de rendimiento, una optimización de la relación entre área foliar y producción, y un aumento en la concentración de compuestos aromáticos.

Este Trabajo Fin de Máster ha dado lugar a la publicación de un *paper* en una revista internacional de alto índice de impacto (Utilization of Vertical Cordon System to Improve Source-Sink Balance and Wine Aroma under Water Shortage Conditions of Maturana Blanca. *Agronomy*. 2022; 12(6):1373. https://doi.org/10.3390/agronomy12061373. JCR – Q1 (Agronomy) / CiteScore – Q2 (Agronomy and Crop Science). Impact Factor: 3.417 (2020). 5-Year Impact Factor: 3.64 (2020)), y a una comunicación en un Congreso nacional (Influencia del sistema de conducción del cultivar Maturana Blanca en la calidad aromática y fenólica del vino. XV Congreso Nacional de Investigación Enológica. GIENOL. 23-26 mayo, 2022. Murcia, España.).

ABSTRACT

In small-clustered vine cultivars, the conditions of success for a hanging form in order to guarantee a sufficient yield and quality level could go through establishing a permanent vertical cordon to enhance vine capacity and to retain a greater number of buds without making a canopy too compact. In this case, it is also important to quantify the main source–sink relationships within the vine in terms of the vine's general responses to water shortage. The influence of two types of spur pruned vines (head-trained (HT) vs. vertical cordon trained (VCT)) was examined in field-grown vines in the local cultivar Maturana Blanca in order to achieve an optimal yield under two irrigation regimes (non-irrigated and irrigated at 30% of ET0). For this vegetative development, yield, fruit composition, and wine volatile compounds were measured. The VCT system has demonstrated to increase yield up to 1.8-fold as compared with the HT system independently of the irrigation regime. Although clear differences were observed in the source-sink ratios between the two training systems, these differences did not affect the ripening of the grapes nor their quality. However, a reduction in berry size and the more exposed clusters in VCT vines resulted in a higher concentration of aromatic compounds in the obtained wines as compared with those of HT vines. This study indicates the improvement of the source to sink ratio of the cv. Maturana Blanca through a change in the training system, which helps to increase light interception, leading to a higher yield potential, an optimization of the leaf area to fruit ratio, and an increase in the concentration of aromatic compounds.

UTILIZATION OF VERTICAL CORDON SYSTEM TO IMPROVE SOURCE-SINK BALANCE AND WINE AROMA UNDER WATER SHORTAGE CONDITIONS OF MATURANA BLANCA

1. INTRODUCTION

Maintaining an appropriate balance between vegetative and reproductive growth is one of the most important management issues in modern viticulture [1]. Better balanced vines are associated with a more open canopy, which is characterized by greater sunlight exposure in the fruiting zone [2]. In this sense, it is believed that a proper source to sink ratio is beneficial for vine balance and grape composition [3]. This ratio can be affected by vineyard attributes and cultural practices such as water supply, training system, presence of cover crops and fertilization, which contribute to controlling grape yield, primary and secondary metabolites of the grapes and, consequently, obtaining different chemical and sensory characteristics of the wines [4–6]. Indeed, aroma is one of the most important sensory characteristics of white wines. The concentration of volatile compounds can influence the quality of white wine. This concentration can be mainly affected by the variety, the vine growing conditions, the quality of ripening and the fermentation technology [7]. The volatile compounds directly derived from grapes are called varietal aromas and determine the varietal typicality of white wine [8].

The wine market is increasingly demanding that wines show the typicity of each wine-growing region and the particularities of the different varieties. In recent years, the Rioja Qualified Denomination (DOCa Rioja, Logroño, Spain) started a project to recover, preserve and study old genotypes that could represent valuable genetic combinations [9,10]. One of the most interesting recovered varieties was the cultivar Maturana Blanca, authorized in 2008 by the D.O.Ca. Rioja [11], which comes from the hybridization between Castellana Blanca (mother) and Savagnin Blanc (father) [12]. Although it is a vigorous variety and, despite its high fertility, it has the disadvantage of low production due to the small size of its clusters [12]. In addition, it shows a high sensitivity to *B. cinerea* due to the great compactness of its clusters. These factors have led to a significant reduction in its cultivation, currently leaving only 39 ha, while years ago, it was one of the most cultivated varieties in the Rioja region. Even so, cv. Maturana Blanca *Vitis vinifera* L. is increasingly used by some Rioja wineries for its valuable grape quality parameters. Its wines have a high alcohol content, compensated by high levels of acidity and low pH, due to a high concentration of tartaric acid, and low contents of malic acid and potassium. Maturana Blanca wines are described as having high aromatic intensity and a predominance of tropical, ripe fruit and floral aromas [13]. In the organoleptic analysis, they are fresh and balanced in the mouth, with slight acidity and medium to high persistence. Generally, its wines are highly valued, and their status as a minority variety can provide personality and typicity [14].

The present study analyses different training systems as adaptation measures to ensure the source-sink balance of Maturana Blanca grapevines, a vigorous variety with low production. Concretely, in small-clustered vine cultivars, such as Pinot Noir [15] or Chardonnay [16], a proper source to sink ratio could go through improving the bud load through a greater number of buds, and therefore, a greater number of clusters per plant, which is generally the major determinant of crop yield [17]. To retain extra buds without making a canopy too compact and to achieve a better microclimate, the choice of a good training system plays an essential role. All aspects of growth, yield, and fruit composition may be affected by the training system [18]. Moreover, several studies reported the influence of training systems on sensory and wine parameters [19]. Vertical cordon (VC) has been used in some winegrowing regions of the world, such as in Italy, where it is known by the name of "cordone vertical speronato", and in California, where it is a kind of "spur-pruned staked vine" [20]. VC is a freely directed training system supported by stakes, where spurs are regularly distributed along the trunk and allows extra buds to be kept for a higher grape yield (Figure 1). Under this training system, the plant canopy and clusters are distributed vertically, achieving a better microclimate and reducing the risk of *Botrytis cinerea* infection. Canopy microclimate depends on the amount and distribution of leaf area in the space, which can be modified by the plant spacing and subsequent pruning and training system [2]. Concretely, the VC training system is characterized by its lower leaf density, maintaining a total leaf area very similar to the external leaf area due to its low number of leaf layers and low percentage of internal leaves [21]. Therefore, VC allows a higher bud load, followed by a greater total leaf area.

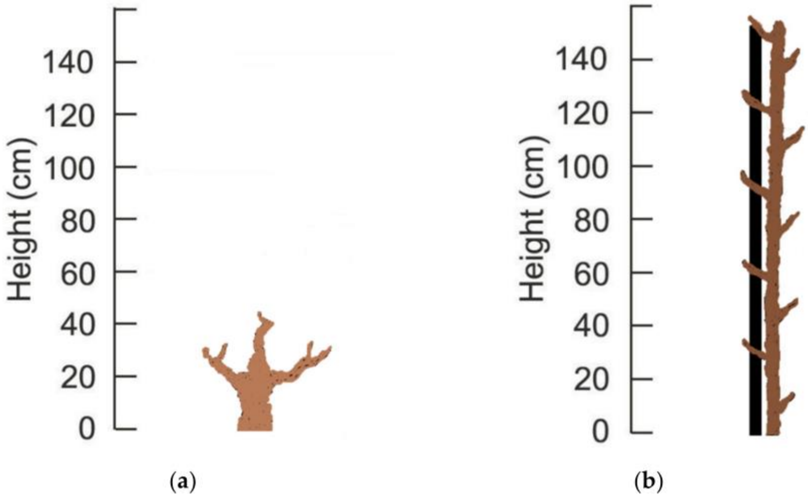

Figure 1. Representations of training systems. (a) Head-trained vine (gobelet); (b) vertical cordon vine.

However, it could be assumed that as leaf area increases, so would the amount of solar radiation intercepted by grapevines and the amount of water consumption [22]. Given the projected climate change [23], with enhanced evapotranspiration demands and a higher number of days with severe heat stress under warmer climates [24], the study of different water levels may also have to be considered to ensure the future sustainability of viticultural yields in the case of VC.

The present study aimed to evaluate the behavior of vertical cordon-trained vines under commercial conditions as an alternative to the traditional goblet training system to ensure a higher number of buds per vine and to test its influence on vine growth. In addition, we analyzed the fruit and wine composition in order to evaluate the optimization of the production of the cv. Maturana Blanca under different water regime conditions.

We hypothesized that a vertical cordon allows better-balanced vines of the cv. Maturana Blanca compared to the traditional goblet training system. The main objectives of this study were to (i) test the impact of the vertical cordon on yield, fruit composition, and wine volatile compounds, (ii) evaluate the interactive effects of the deficit irrigation and the training system, and (iii) contribute to improving the varietal typicity of the cv. Maturana Blanca and favor its use by Rioja wineries.

2. MATERIALS AND METHODS

2.1 Plant Material and Irrigation Treatments

The experiment was carried out in a 2021 vintage in a commercial vineyard located in San Vicente de la Sonsierra (La Rioja), with a semi-arid continental climate. The grapevines (*V. vinifera* cv. Maturana Blanca) were 6 years old, grafted onto R-110 rootstock. The rows run from N-W to S-E, and the planting distance was 2.4 m between rows and 1.3 m between vines (3205 plants ha^{-1}).

Grapevines were trained on a free-standing system, supported by single stakes. The treatments consisted of two different spur-pruning training systems: traditional goblet pruned to five spurs (10 buds) per vine named as head-trained (HT), and vertical cordon pruned to ten spurs (20 buds) per vine named as vertical cordon trained (VCT). Both systems were managed in accordance with standard viticulture practices of Rioja appellation [25]

Moreover, two different irrigation treatments were applied: moderate-watered plants (MW), which received around 3 L per plant and day (Kc of 0.3), and water stress (WS) plants, which consisted of withholding water during the whole season. Irrigation started in July and finished in September. Evapotranspiration demand (ET_0) was calculated from the Penman-Monteith equation [26], and the amount of applied water was every 10 to 12 days. Over the experimental period, the cumulative irrigation volumes were 96.6 mm for the irrigated treatments, while no irrigation was provided in the WS treatments.

The combination of both imposed treatments (training system and irrigation) was named as follows: (i) head-trained–moderate watered at 30% of ET_0 (HT-MW), (ii) head-trained–water-stressed (HT-WS), (iii) vertical cordon trained–moderate watered at 30% of ET_0 (VCT-MW) and (iv) vertical cordon trained-water-stressed (VCT-WS). The experimental design was a randomized complete block divided into three replicates per treatment. Each replicate consisted of 4 vines. One row was used as a buffer to separate irrigated and non-irrigated vines.

Weather data were provided by an automatic meteorological station belonging to the Agroclimatic Information Service of La Rioja (SIAR) located close to the experimental site. Yearly rainfall from harvest to harvest was 467.7 mm and the average temperature during this period was 12.8 °C. The climatic conditions during the vegetative growth period (from April to the end of September) were 198.2 mm and 17.0 °C, respectively.

2.2 Grapevine Water Status

Midday leaf water potential (Ψ_{md}) was measured at three different development stages designated by the BBCH code of Eichhorn and Lorenz (1977) [27] (8 June (BBCH 65), 20 August (BBCH 81), 17 September (BBCH 85)). Water potentials were measured with a pressure chamber (Soil moisture Equipment, Corp., Santa Barbara, CA, USA) on one leaf from six well-established plants per treatment.

2.3 Vegetative Growth Determinations

Total leaf area (LA) was estimated in six vines per treatment-combination three weeks before veraison when shoot growth had ceased. The total leaf area was calculated according to the non-destructive method previously described by Sánchez de Miguel et al. (2010, 2011) [28,29]. For this, primary shoot length (PSL) and the number of lateral shoots (LT) were also measured by manual determinations.

At first, the relationship between the length of the main vine and the leaf area was established for the cultivar Maturana Blanca. For this, 18 shoots were randomly sampled from the vineyard, and the length of the main vein and its respective leaf area was measured. The area of each leaf was measured by a WinDias image analysis system (Delta-T Devices, Cambridge, UK). Microsoft Excel v.2016 software was used to perform a potential regression between individual leaf area (ILA, cm^2) and main vein length (MVL, cm), thereby obtaining the equation required to calculate the LA:

$$\text{ILA} = 1.4949 \times \text{MVL}1.9525 \ (R^2 = 0.9579), \qquad (1)$$

Later, in three shoots per vine in a total of six plants per treatment, MVL of the largest and the smallest leaves and the number of leaves per shoot were determined in both the primary and lateral shoots to finally obtain the total LA.

To calculate the total LA, the MVL data were converted into ILA values using Equation (1), obtaining the area of the largest main leaf (L1) and the area of the smallest main leaf (S1), as well as the area of the largest lateral leaf (L2) and of the smallest lateral leaf (S2). Through these measurements, we obtained the average leaf area as A = (L + S)/2, both in the main leaf (A1) and the lateral leaf (A2). With the obtained number of leaves per shoot (NL), we calculated the average leaf area per shoot (ALA = A x NL). Finally, the total leaf area per vine was obtained by multiplying the number of shoots by ALA.

Pruning weight (PW) was determined after the growth cycle within each plot separately, having a total of 6 replicates per treatment. Furthermore, leaf area-to-yield ratio (LA/Y) and yield-to-pruning weight ratio (Y/PW) per vine were also calculated.

2.4 Yield Components

The harvest date was in accordance with the grower's practice in the area when °Brix reached 23–24. At harvest, the number of clusters and their total yield (kg $vine^{-1}$), cluster weight, berry number per cluster, and berry weights were recorded on 12 plants per treatment. The number of berries per cluster was calculated, taking into account both the cluster weight and berry weight. A random sample of 200 berries from each plant was collected to measure the average berry weight.

2.5 Fruit Composition Analysis

In each of the three replicates per treatment, 500 berries were randomly sampled to analyze the evolution of technological and phenolic maturity.

The obtained musts were physico-chemically characterized by determining total soluble solids (TSS), probable alcohol (PA), pH, titratable acidity (TA), malic acid (MA), and potassium (K) according to the OIV (2021) [30], and tartaric acid according to the Rebelein method [31]. Yeast assimilable nitrogen (YAN) was determined according to the method described by Aerny (1996) [32].

Total polyphenol index (TPI) was determined by spectrophotometry in accordance with Ribereau-Gayon et al. (2000) [33], and they were expressed in terms of absorbance units (UA).

2.6 Winemaking

Plants were harvested by hand at their optimal ripening stage and in good sanitary conditions; they were placed in 10-kg plastic boxes, immediately transported to the experimental winery and processed. The grapes of each treatment were vinified in triplicate, which is one vinification per replicate. Grapes were destemmed, crushed and directly pressed in a pneumatic press. The maximum pressure was 2.5 kg cm^{-2}, and one pressing cycle was carried out. The free run juice was quickly sulfited (0.06 g L^{-1}), and it was clarified at 8 °C for 24 h after adding pectolytic enzymes (0.02 g L^{-1}, Lafazym CL, Laffort, Bordeaux, France). The clean must with 50 to 100 NTU was transferred to 15 L tanks and inoculated with 0.25 g L^{-1} of commercial yeasts (Zymaflore X16, Laffort, Bordeaux, France). Fermentations were carried out at 18 °C. The end of fermentation was determined by measuring reducing sugars (<2.5 g L^{-1}). Then, the wines were racked, sulfited (0.04 g L^{-1}) and stored at 5 °C for one month to favor their stabilization.

2.7 Analysis of Wine Volatile Composition

Volatile families were analyzed by gas chromatography–mass spectrometry (GC-MS) in triplicate after extraction with dichloromethane and with 4-nonanol as the internal standard, according to Coelho et al. (2020) [34]. A gas chromatograph Varian 3800 (Varian Inc., Walnut Creek, CA, USA) with a 1079 injector and an ion-trap mass spectrometer Varian Saturn 2000 was used. A 1 µL injection was made in splitless mode (30 s) in a Varian Factor Four VF-Wax ms column (30 m × 0.15 mm; 0.15 µm film thickness) with helium UltraPlus 5 ×(Praxair) at 1.3 mL min^{-1} as the carrier gas, and the rest of the conditions described by Coelho et al. (2020) [34]. The identification of compounds was performed using the software MS Workstation version 6.9 (Varian Inc., Walnut Creek, CA, USA), by comparing their mass spectra and retention indices with those of pure standard compounds. The compounds were quantified in terms of 4-nonanol equivalents. Pure standard compounds were purchased from Sigma-Aldrich (Darmstadt, Germany) and had a purity higher than 98%.

The odor activity value (OAV) was determined to evaluate the contribution of each compound to the aroma of the wine. The OAV was calculated as the ratio between the concentration of each compound and its odor threshold. The perception threshold used in this study was found in the literature.

3. RESULTS

3.1 Climate and Irrigation Treatments

The climate at the vineyard site is continental and semi-arid with an average rainfall of 562 mm, of which about 38% falls during the vegetative growth period. However, the experimental period was characterized by being a relatively drier season than the average (Table 1), especially during the summer, with total rainfall of 39 mm from 21 June 2021 to 21 September 2021. Considering the irrigation volumes carried out during the vegetative growth period, the VCT-MW and HT-MW vines received 49% more water than WS plants.

Table 1. Monthly climatic conditions measured during the experimental period in 2021. Values represented are mean temperature (T° mean, °C), maximum temperature (T° max, °C), minimum temperature (T° min, °C), reference evapotranspiration (ET0, mm) and rainfall (mm) per month. Climatic balance for the experimental season in 2021 and the average for the 2005–2021 period (from harvest to harvest) are also shown.

	T° mean	**T° max**	**T° min**	**ET_0 (mm)**	**Rainfall (mm)**
April	10.3	23.2	−1	87.6	44
May	14.3	30.1	2	130.1	30.7
June	18.1	33.4	7.5	142.2	87.9
July	20.1	37.3	9.3	162.8	0.7
August	20.4	40.4	9.2	149.5	4.6
September	18.6	31.1	7.9	93.7	30.3
2021	12.8	40.4	−2.2	1033.7	467.7
Average (2005–2021)	12.5	40.8	−9.2	1097.1	562.6

3.2 Differences in Vegetative Growth and Leaf Area

An increase in the number of spurs per vine and the number of main shoots per vine were measured in the vertical cordon trained (VCT) plants compared with head-trained(HT) plants because of the different training systems (Table 2). Consequently, total leaf area was significantly reduced in HT vines, reflecting the different management techniques during the vineyard establishment. However, primary shoot length and number of lateral shoots per vine were higher in the HT treatments. Indeed, differences in pruning weight were not observed between HT and VCT systems, probably because of the compensatory effect of HT vines (Table 2).

Table 2. Mean values of several vegetative growth components of the different treatments. LA (leaf area, m^2 $vine^{-1}$), PSL (primary shoot length, cm), LT (lateral shoots per vine, lateral shoots $vine^{-1}$), PW (pruning weight, kg $vine^{-1}$), SP (number of spurs per vine, spurs $vine^{-1}$), and NMS (number of main shoots per vine, shoots $vine^{-1}$).

	LA	PSL	LT	PW	SP	NMS
HT-MW	3.99 ± 1.02	139.3 ± 34.3	9.78 ± 3.10	0.85 ± 0.01	5.75 ± 0.35	12.2 ± 0.31
HT-WS	3.95 ± 0.51	161.5 ± 28.8	9.39 ± 3.09	0.75 ± 0.05	5.50 ± 0.00	11.3 ± 0.35
VCT-MW	5.99 ± 0.94	107.6 ± 23.9	7.37 ± 2.21	0.80 ± 0.07	10.8 ± 0.47	21.8 ± 0.47
VCT-WS	5.93 ± 0.88	121.7 ± 31.2	7.06 ± 2.82	0.89 ± 0.07	10.2 ± 0.12	20.8 ± 0.82
TS	***	***	*	ns	***	***
I	ns	*	ns	ns	ns	ns
TS × I	ns	ns	ns	ns	ns	ns

Values are means ± standard error of six vines per treatment. Significant differences for training system (TS), irrigation (I), and TS × I were analyzed by two-way ANOVA in randomized blocks design (ns, not significant; *, $p \leq 0.05$; ***, $p \leq 0.001$).

Finally, the water stress increased the length of the main shoots in both training systems, while no other parameters were significantly affected (Table 2).

3.3 Vine Water Status

In all four treatments, water potential (Ψ_{md}) tended to decrease from flowering towards veraison; after that, values slightly decreased in VCT vines or even increased in HT vines (Table 3). During flowering, minimum Ψ_{md} values were about -1.06 MPa, and no differences were found neither between training systems nor between irrigation treatments. In veraison, water-stressed plants reduced their Ψ_{md} values up to 19% in VCT and 14% in HT as compared with irrigated plants; however, differences between training systems were not significant. During ripening, when minimum Ψ_{md} values were reached, differences between irrigation treatments were also significant. Moreover, during this stage, Ψ_{md} was also affected by the training system, showing lower values for the VCT vines as compared to HT vines. Moreover, a downward trend was observed in the Ψ_{md} of the VCT vines, unlike the HT vines, which took higher values than in the previous stage.

Table 3. Seasonal variation of midday water potential (Ψmd) for cv. Maturana Blanca in the head- trained irrigated (HT-MW), head-trained stress (HT-WS), vertical cordon trained irrigated (VCT-MW) and vertical cordon trained stress (VCT-WS).

	Midday Leaf Water Potential (MPa)		
	Flowering	Veraison	Ripening
HT-MW	−1.03 ± 0.04	−1.41 ± 0.08	−1.39 ± 0.03
HT-WS	−1.06 ± 0.05	−1.60 ± 0.08	−1.56 ± 0.11
VCT-MW	−0.98 ± 0.07	−1.34 ± 0.03	−1.51 ± 0.03
VCT-WS	−1.06 ± 0.05	−1.60 ± 0.10	−1.64 ± 0.07
TS	ns	ns	**
I	ns	***	***
TS × I	ns	ns	ns

Values are means ± standard error of six vines per treatment. Significant differences for training system (TS), irrigation (I), and TS × I were analyzed by two-way ANOVA in randomized blocks design (ns, not significant; **, $p \leq 0.01$; ***, $p \leq 0.001$).

3.4 Yield Components

Differences in the training system resulted in high differences in yield. The yield obtained by the VCT plants increased up to 83% as compared with HT plants. As expected, these differences were mainly due to the higher number of main shoots per vine in VCT than in HT plants, and not because of the higher cluster weight or cluster per shoot, as it is shown in Table 4. Although berry weight increased in HT plants, this was not enough to counteract the higher number of berries per cluster in VCT plants, resulting in no differences in cluster weight between training systems. In general, water withholding had a much weaker effect on yield components than the number of shoots per plant. However, some differences in yield were observed between irrigation treatments because of the lower berry weight and the slight reduction in the number of clusters per shoot and cluster weight in water-stressed plants compared to moderate-irrigated plants, leading to a 25% reduction in yield. In this case, no differences were observed in clusters per shoot nor in cluster weight, but there were differences in berry weight.

Table 4. Yield and yield components of the different treatments.

	Yield	**Clusters Per Shoot**	**Cluster Weight**	**Berry Weight**	**Berries Per Cluster**	**Leaf Area: Yield**	**Yield: Pruning Weight**
	kg Vine^{-1}	**Clusters Shoot^{-1}**	**g Cluster^{-1}**	**g**	**Berries Cluster^{-1}**	**m^2 kg^{-1}**	**kg kg^{-1}**
HT-MW	2.19 ± 0.39	1.52 ± 0.25	117.7 ± 4.1	1.48 ± 0.03	79.88 ± 4.23	1.82 ± 0.35	2.57 ± 0.46
HT-WS	1.58 ± 0.25	1.36 ± 0.16	102.7 ± 6.5	1.22 ± 0.09	84.14 ± 1.21	2.72 ± 0.54	2.15 ± 0.50
VCT-MW	3.95 ± 0.27	1.70 ± 0.10	108.9 ± 3.9	1.20 ± 0.04	90.52 ± 3.74	1.55 ± 0.14	4.95 ± 0.35
VCT-WS	2.97 ± 0.26	1.40 ± 0.09	102.6 ± 15	1.06 ± 0.11	96.30 ± 4.95	2.02 ± 0.26	3.38 ± 0.48
TS	***	ns	ns	**	**	*	***
I	**	ns	ns	**	ns	*	*
TS × I	ns	ns	ns	ns	ns	ns	ns

Values are means ± standard error of six vines per treatment. Significant differences for training system (TS), irrigation (I), and TS x I were analyzed by two-way ANOVA in randomized blocks design (ns, not significant; *, $p \leq 0.05$; **, $p \leq 0.01$; ***, $p \leq 0.001$).

In this study, two different indices were used to estimate the vine balance and both were differently affected by either the irrigation treatment and the training system (Table 4). On the one side, the leaf area-to-yield ratio was slightly affected by the training system, but the marked difference in yield between irrigated and non-irrigated plants led to obtaining up to 49 and 30% higher ratios in the non-irrigated vines as compared to the irrigated ones in HT and VCT plants, respectively. In WS plants, to reach 23–24 Brix required 2.02 to 2.72 m^2 leaf area per kg fruit, whereas MW plants needed 1.55 to 1.82 m^2 leaf area per kg fruit to reach the same Brix. Conversely, on the other side, the yield-to-pruning weight ratio, also known as the Ravaz index, was higher in VCT vines as compared with HT vines, with the maximum value in the VCT-MW treatment. Moderate-watered vines showed a higher value in both training systems.

3.5 Must Quality

In general, the effect of the different treatments on all must composition parameters was slightly significant (Table 5). Concerning the technological maturity, there were only significant differences between treatments in must pH and titratable acidity. Must pH was lower in VCT vines, but no differences were observed for the different water regimes. Consequently, titratable acidity was higher in musts from VCT vines, but in this case, there were differences in irrigation treatment, with lower values in irrigated plants. Total soluble solids were not affected by the training system nor by irrigation. The concentrations of the main organic acids were differentially affected by the treatments. Thus, malic acid concentration only showed differences between training systems, with lower values for musts from VCT vines compared to HT vines. However, tartaric acid concentration showed differences between irrigation treatments but not between training systems. The concentration of this acid was higher in the musts from vines subjected to greater water stress.

Table 5. Parameters of must composition at harvest for cv. Maturana Blanca grapes for each treatment. Abbreviations are as follows: TSS (total soluble solids, °Brix), PA (probable alcohol % v/v), TA (titratable acidity, g L^{-1} of tartaric acid), Tart. acid (tartaric acid, g L^{-1}), MA (malic acid, g L^{-1}), K (potassium, mg L^{-1}), YAN (yeast-assimilable nitrogen, mg N L^{-1}), TPI (total polyphenol index, AU).

	TSS	PA	pH	TA	Tart. Acid	MA	K	YAN	TPI
HT-MW	23.23 ± 0.1	13.61 ± 0.1	3.24 ± 0.05	4.22 ± 0.04	6.89 ± 0.21	0.40 ± 0.03	828.31 ± 67.17	246.33 ± 8.50	47.00 ± 4.54
HT-WS	23.33 ± 0.5	13.68 ± 0.4	3.26 ± 0.01	4.32 ± 0.16	7.27 ± 0.41	0.28 ± 0.05	810.31 ± 36.34	292.67 ± 14.38	63.03 ± 2.11
VCT-MW	22.73 ± 0.7	13.27 ± 0.5	3.18 ± 0.03	4.33 ± 0.07	6.59 ± 0.21	0.24 ± 0.00	700.68 ± 15.88	276.33 ± 22.22	51.27 ± 5.65
VCT-WS	23.23 ± 0.3	13.62 ± 0.2	3.14 ± 0.04	4.81 ± 0.28	7.17 ± 0.16	0.25 ± 0.05	756.35 ± 15.84	258.00 ± 15.94	65.83 ± 1.59
TS	ns	ns	**	**	ns	**	*	ns	ns
I	ns	ns	ns	*	*	ns	ns	ns	**
TS × I	ns	ns	ns	ns	ns	*	ns	*	ns

Values are means ± standard error of three vines per treatment. Significant differences for training system (TS), irrigation (I), and TS × I were analyzed by two-way ANOVA in a randomized block design (ns, not significant; *, $p \leq 0.05$; **, $p \leq 0.01$).

Must potassium concentrations increased in HT vines compared with VCT vines, in line with the lower pH values, but the irrigation treatments had no influence on potassium concentration. YAN concentration ranged from 258 to 293 mg N L-1, but the different treatments did not clearly affect this variable. TPI showed higher values for drought treatments in both training systems.

3.6 Wine Volatile Composition

Figure 2 shows the combined effect of the training system and the water regimen on Maturana Blanca wine volatile concentrations. The volatile composition has been organized into eight chemical families: higher alcohols, C6 compounds, terpenes + C13- norisoprenoids, ethyl esters, acetate esters, fatty acids, lactones, and volatile phenols. The training system induced significant changes in the concentration of all the studied groups of compounds. Thus, wines from VCT vines showed higher concentrations of all volatile families of compounds (between 16 and 144%). Additionally, slight variations of volatiles were observed because of irrigation in both training systems. In general, a tendency to increase the concentration of the volatile families studied was observed when irrigation was applied in VCT vines. On the other hand, in wines from HT vines, the application of irrigation caused an unequal effect depending on the family studied.

Table 6 shows the influence of the training system and irrigation treatments (HT-MW, HT-WS, VCT-MW, and VCT-WS) on the individual volatile compounds identified and quantified by GC-MS in Maturana Blanca wines (expressed as µg L^{-1}). A total of 44 volatile compounds were detected, and 43 of them were detected in all wines (Table X). Alcohols were the principal group of volatile compounds (> 81% of the total volatile concentration) in Maturana Blanca wines, followed by acetate esters, fatty acids, and ethyl esters (Figure 2). Table 7 shows the odor threshold and descriptor of each individual value. The odor activity value (OAV) is a parameter widely used to evaluate the contribution of individual volatiles to the overall aroma of wine [35]. In general, the OAV greater than or equal to the unit indicates an active odor. In addition, volatile compounds with OAVs above 0.1 indicate that these volatiles played an important role in the overall aroma of these wines [36].

Within the family of higher alcohols, a total of eight compounds were detected: 1-propanol, 1-butanol, isobutanol, isopentanol, 3-methyl-1-pentanol, benzyl alcohol, 2-phenylethanol, and methionol. All Maturana Blanca wines were characterized as having high contents of isopentanol (3-methyl-1-butanol) and 2-phenylethanol, both above their odor threshold. The highest values of both compounds were found in wines from VCT-MW vines. Moreover, higher values of isopentanol were also found in wines from VCT-WS vines compared to wines from HT vines. The compounds 1-propanol and isobutanol (2-methyl-1-propanol), were also found in significant concentrations, although both were well below their odor thresholds. The rest of the higher alcohols showed concentrations below 100 µg L^{-1}.

Four C6 alcohols were identified in the different wines: 1-hexanol, *trans*-3-hexen-1-ol, *cis*-3-hexen-1-ol, and *trans*-2-hexen-1-ol, with none of them above the threshold. The VCT system led the wines to have higher concentrations of C6 compounds as compared with HT vines. The irrigation did not affect the C6 alcohol concentration; however, an interaction exists with the training system. In this case, irrigation increased the 1-hexanol concentration in wines from VCT vines, while it decreased this component in wines from HT vines.

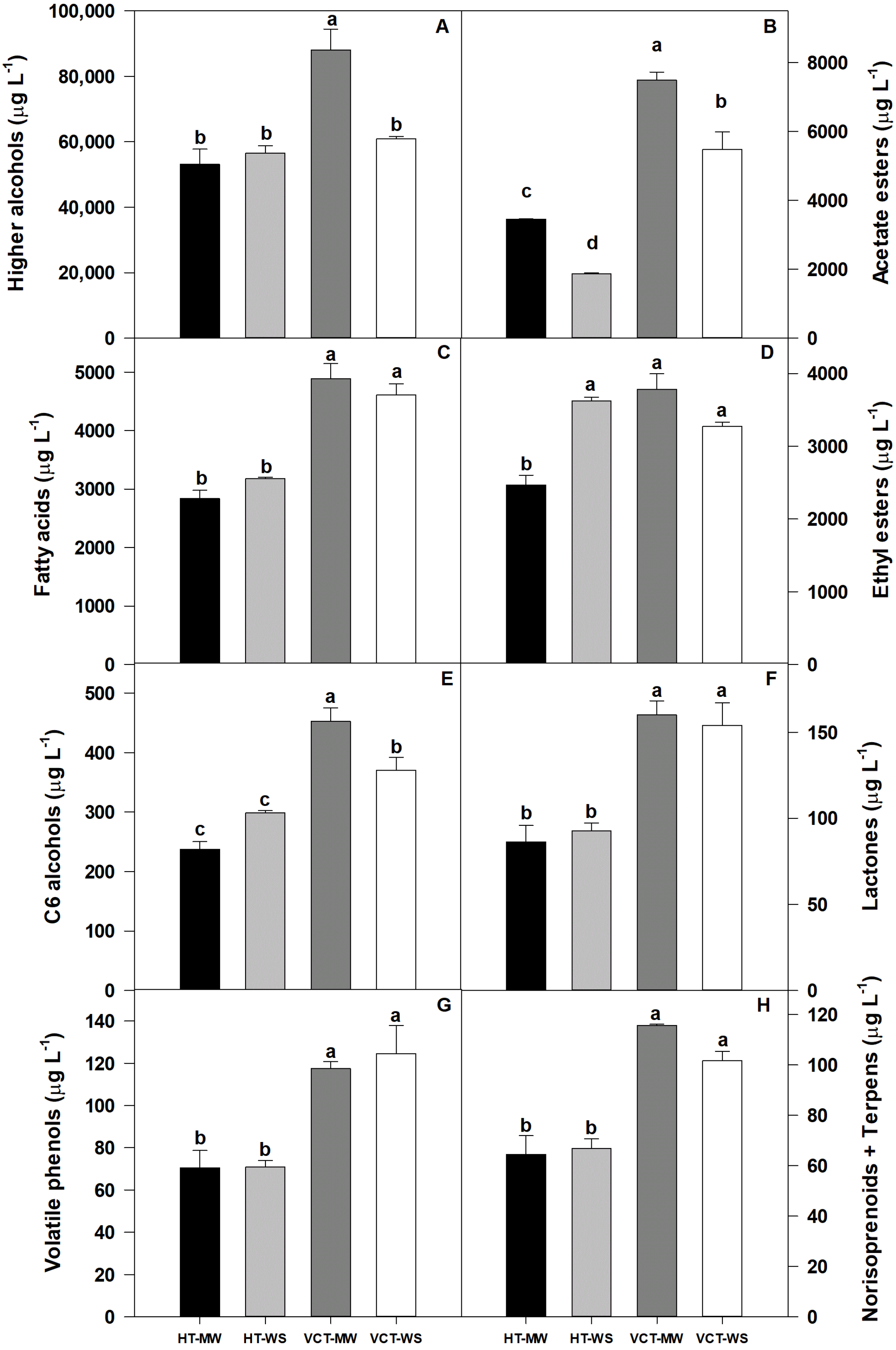

Figure 2. Maturana Blanca wine volatile families (expressed in µg L^{-1}): (**A**) alcohols, (**B**) acetates esters, (**C**) volatile acids (**D**) ethyl esters, (**E**) C6 compounds, (**F**) lactones, (**G**) volatile phenols and (**H**) norisoprenoids + terpenes. Values are mean ± standard error of three replicates. Letters denote statistic significant differences between treatments ($p < 0.05$).

Table 6. Concentration (μg L^{-1}) of volatile compounds of Maturana Blanca wines obtained by the different treatments.

Compounds	HT-MW	HT-WS	VCT-MW	VCT-WS	TS	I	TS × I
Higher alcohols							
1-Propanol	103.79 ± 14.23	180.82 ± 17.18	399.55 ± 37.17	320.42 ± 66.52	**	ns	ns
1-Butanol	24.97 ± 2.80	38.80 ± 1.56	41.60 ± 4.26	38.85 ± 7.05	ns	ns	ns
Isobutanol	777.13 ± 98.78	852.32 ± 40.02	1309.44 ± 121.38	1348.60 ± 243.62	*	ns	ns
Isopentanol	16.164.55 ± 1734.46	18.261.18 ± 584.11	28.444.31 ± 1684.55	26.369.24 ± 2238.56	**	ns	ns
3-Methyl-1-pentanol	13.62 ± 1.19	19.82 ± 0.53	16.05 ± 0.82	13.11 ± 0.92	ns	ns	**
Benzyl alcohol	23.10 ± 2.37	31.35 ± 1.43	39.09 ± 2.97	21.95 ± 0.75	ns	ns	**
2-Phenylethanol	35.867.42 ± 2769.13	37.085.85 ± 1553.82	57.775.58 ± 4485.54	32.759.28 ± 1856.92	*	*	*
Methionol	96.50 ± 14.54	69.25 ± 4.26	76.64 ± 6.36	41.45 ± 3.59	*	*	ns
C6 compounds							
1-hexanol	194.88 ± 15.27	248.59 ± 2.65	376.01 ± 17.37	300.72 ± 30.43	***	ns	*
trans-3-Hexen-1-ol	36.16 ± 3.02	42.57 ± 2.31	62.97 ± 3.15	60.53 ± 2.20	***	ns	ns
cis-3-Hexen-1-ol	5.89 ± 0.26	6.91 ± 0.06	12.74 ± 1.66	8.80 ± 1.67	*	ns	ns
trans-2-Hexen-1-ol	0.16 ± 0.07	0.38 ± 0.42	0.59 ± 0.46	0.41 ± 0.39	ns	ns	ns
Terpenes + C13 norisoprenoids							
β-Citronellol	0.50 ± 0.45	1.61 ± 2.10	1.67 ± 2.10	1.74 ± 1.63	ns	ns	ns
Nerol	49.11 ± 10.04	46.76 ± 7.13	88.89 ± 5.56	81.51 ± 9.71	**	ns	ns
Geraniol	5.65 ± 0.29	6.56 ± 0.02	5.68 ± 0.10	4.84 ± 0.30	**	ns	**
β-pinene	0.19 ± 0.09	0.29 ± 0.20	0.38 ± 0.30	0.39 ± 0.43	ns	ns	ns
Linalool	2.78 ± 0.44	4.58 ± 0.07	5.87 ± 1.49	4.42 ± 0.66	ns	ns	ns
Terpinolene	nd	nd	0.35 ± 0.49	nd	ns	ns	ns
α-Ionone	0.21 ± 0.30	0.49 ± 0.70	1.81 ± 0.89	0.80 ± 0.85	ns	ns	ns
β-Ionone	0.08 ± 0.06	0.11 ± 0.16	0.24 ± 0.23	0.24 ± 0.24	ns	ns	ns
Damascenone	6.29 ± 1.52	6.51 ± 0.81	8.70 ± 1.40	6.66 ± 1.66	*	ns	ns
Ethyl esters							
Ethyl butanoate	122.96 ± 4.23	119.07 ± 1.88	250.52 ± 16.07	222.53 ± 27.21	***	ns	ns
Ethyl 2-methylbutyrate	5.47 ± 0.18	6.56 ± 0.18	7.82 ± 0.92	6.04 ± 0.04	ns	ns	*
Ethyl hexanoate	539.12 ± 9.38	589.15 ± 2.99	856.60 ± 80.77	840.66 ± 131.10	**	ns	ns
Ethyl lactate	683.50 ± 118.27	1119.24 ± 112.04	1456.27 ± 118.74	1221.16 ± 215.75	*	ns	*
Ethyl isovalerate	8.61 ± 1.61	10.13 ± 0.69	15.21 ± 1.73	9.44 ± 1.21	*	ns	*
Ethyl octanoate	528.96 ± 51.86	553.05 ± 1.95	768.21 ± 63.73	688.15 ± 94.30	*	ns	ns
Ethyl decanoate	25.87 ± 2.14	25.46 ± 0.44	37.72 ± 3.78	40.46 ± 2.84	**	ns	ns
Diethyl succinate	541.87 ± 1.48	1190.07 ± 44.87	370.87 ± 16.47	228.50 ± 37.08	***	***	***

Table 6. *Cont*.

Compounds	HT-MW	HT-WS	VCT-MW	VCT-WS	TS	I	TS × I
Acetate esters							
Isoamyl acetate	2270.49 ± 43.67	1116.69 ± 25.99	5436.94 ± 281.29	4284.80 ± 518.20	***	**	ns
Pheniethyl acetate	1148.52 ± 25.03	733.56 ± 8.71	1947.42 ± 49.11	1116.84 ± 191.42	***	***	*
Hexyl acetate	33.88 ± 5.09	12.69 ± 0.18	97.84 ± 4.87	77.48 ± 12.19	***	*	ns
Fatty acids							
Butanoic acid	61.01 ± 9.30	82.92 ± 8.15	122.04 ± 12.27	128.05 ± 31.42	*	ns	ns
Propanoic acid	7.37 ± 1.49	10.25 ± 1.47	19.28 ± 2.56	17.12 ± 4.89	*	ns	ns
Isobutyric acid	60.69 ± 11.50	76.82 ± 4.68	105.62 ± 4.73	108.98 ± 25.79	*	ns	ns
Hexanoic acid	1219.41 ± 115.14	1371.61 ± 30.23	2166.27 ± 162.22	2164.70 ± 79.68	***	ns	ns
Octanoic acid	1081.82 ± 7.56	1156.53 ± 23.26	1844.08 ± 124.45	1628.31 ± 306.78	**	ns	ns
cis-Geranic acid	32.30 ± 5.06	40.07 ± 3.33	42.39 ± 3.44	28.08 ± 14.45	ns	ns	ns
trans-Geranic acid	0.17 ± 0.23	0.57 ± 0.22	0.29 ± 0.14	0.26 ± 0.17	ns	ns	ns
Lactones							
γ-Butirolactone	77.91 ± 14.43	87.21 ± 6.46	154.55 ± 12.51	149.56 ± 18.97	**	ns	ns
Volatile phenols							
4-Vinylguaiacol	50.58 ± 7.57	52.58 ± 0.10	82.12 ± 1.30	73.49 ± 9.32	**	ns	ns
4-Vinylphenol	19.59 ± 3.66	17.63 ± 3.98	34.74 ± 2.70	50.71 ± 9.40	**	ns	ns
Carbonyl compounds							
Acetoin	80.09 ± 20.04	242.31 ± 35.88	69.04 ± 6.56	59.45 ± 13.21	**	**	**
Aldehydes							
Vanillin	0.72 ± 0.37	0.84 ±.0.01	2.17 ± 0.18	1.58 ± 0.50	**	ns	ns
trans-Geranic acid	0.17 ± 0.23	0.57 ± 0.22	0.29 ± 0.14	0.26 ± 0.17	ns	ns	ns
Lactones							
γ-Butirolactone	77.91 ± 14.43	87.21 ± 6.46	154.55 ± 12.51	149.56 ± 18.97	**	ns	ns
Volatile phenols							
4-Vinylguaiacol	50.58 ± 7.57	52.58 ± 0.10	82.12 ± 1.30	73.49 ± 9.32	**	ns	ns

Values are means ± standard error of three samples. Significant differences for training system (TS), irrigation (I), and TS × I were analyzed by two-way ANOVA in a randomized block design (ns, not significant; *, $p \leq 0.05$; **, $p \leq 0.01$; ***, $p \leq 0.001$). nd: not detected.

Table 7. Odor activity values (OAV) of Maturana Blanca wines obtained by the different treatments.

Compounds	**Odor Descriptor**	**Odor Threshold (μg L^{-1})**	**Ref.**	**OAV**				**TS**	**I**	**TS × I**
				HT-MW	**HT-WS**	**VCT-MW**	**VCT-WS**			
Higher alcohols										
1-Propanol	Alcohol, ripe fruit	306,000	[37]	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	*	ns	ns
1-Butanol	Medicinal, phenolic	150,000	[37]	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	ns	ns	ns
Isobutanol	Fusel	40,000	[38]	0.02 ± 0.00	0.02 ± 0.00	0.03 ± 0.00	0.03 ± 0.01	*	ns	ns
Isopentanol	Alcohol, banana	7000	[39]	**2.31 ± 0.25**	**2.61 ± 0.08**	**4.06 ± 0.24**	**3.77 ± 0.32**	**	ns	ns
3-Methyl-1-pentanol	Herbaceous, cocoa	50,000	[40]	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	ns	ns	**
Benzyl alcohol	Caramel, fruity	200,000	[41]	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	ns	ns	**
2-Phenylethanol	Floral, roses, lilac	10.000	[42]	**3.59 ± 0.28**	**3.71 ± 0.16**	**5.78 ± 0.45**	**3.28 ± 0.19**	*	*	*
Methionol	Baked vegetables	1000	[43]	0.10 ± 0.01	0.07 ± 0.00	0.08 ± 0.01	0.04 ± 0.00	*	*	ns
C6 compounds										
1-hexanol	Green, cut grass	8000	[40]	0.02 ± 0.00	0.03 ± 0.00	0.05 ± 0.00	0.04 ± 0.00	***	ns	*
trans-3-Hexen-1-ol	Green, floral	400	[44]	0.09 ± 0.01	0.11 ± 0.00	0.16 ± 0.01	0.15 ± 0.00	***	ns	ns
cis-3-Hexen-1-ol	Green, cut grass	400	[40]	0.01 ± 0.00	0.02 ± 0.00	0.03 ± 0.00	0.02 ± 0.00	*	ns	ns
trans-2-Hexen-1-ol	Herbaceous, green	15,000	[45]	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	ns	ns	ns
Terpenes + C13 norisoprenoids										
β-Citronellol	Rose	100	[46]	0.00 ± 0.00	0.02 ± 0.10	0.02 ± 0.01	0.02 ± 0.01	ns	ns	ns
Nerol	Fresh, sweet, rose-like	500	[47]	0.10 ± 0.01	0.09 ± 0.01	0.18 ± 0.01	0.16 ± 0.01	**	ns	ns
Geraniol	Roses, geranium	20	[36]	0.28 ± 0.01	0.33 ± 0.00	0.28 ± 0.03	0.24 ± 0.01	**	ns	**
β-pinene	Woody	1500	[47]	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	ns	ns	ns
Linalool	Green, floral, sweet	15	[47]	0.19 ± 0.02	0.31 ± 0.00	0.39 ± 0.07	0.29 ± 0.03	ns	ns	ns
Terpinolene	Woody, sweet, citrus	41	[47]	0.00 ± 0.00	0.00 ± 0.00	0.01 ± 0.01	0.00 ± 0.00	ns	ns	ns
α-Ionone	Sweet fruit	2.6	[40]	0.08 ± 0.08	0.19 ± 0.19	0.69 ± 0.24	0.31 ± 0.23	ns	ns	ns
β-Ionone	Violets, rose	0.09	[40]	0.89 ± 0.44	**1.25 ± 1.25**	**2.67 ± 1.79**	**2.94 ± 1.90**	ns	ns	ns
Damascenone	Sweet, exotic flowers, stewed	0.14	[48]	**38.80 ± 2.24**	**43.25 ± 1.40**	**67.66 ± 2.82**	**52.40 ± 8.40**	*	ns	ns
Ethyl esters										
Ethyl butanoate	Papaya, apple, sweet	20	[49]	**6.15 ± 0.15**	**5.95 ± 0.07**	**12.53 ± 0.57**	**11.13 ± 0.96**	***	ns	ns
Ethyl 2-methylbutyrate	Fruity, strawberry, apple, blackberry	2	[50]	**2.73 ± 0.06**	**3.28 ± 0.06**	**3.91 ± 0.33**	**3.02 ± 0.01**	ns	ns	*
Ethyl hexanoate	Apple, fruity, sweet	14	[49]	**38.51 ± 0.47**	**42.08 ± 0.15**	**61.19 ± 4.08**	**60.05 ± 6.62**	**	ns	ns
Ethyl lactate	Strawberry, raspberry	154,000	[42]	0.00 ± 0.00	0.01 ± 0.00	0.01 ± 0.00	0.01 ± 0.00	***	***	***
Ethyl isovalerate	Fruity, strawberry, apple	0.7	[50]	**12.30 ± 1.63**	**14.47 ± 0.69**	**21.73 ±1.75**	**13.48 ± 1.23**	*	ns	*

Table 7. *Cont.*

Compounds	**Odor Descriptor**	**Odor Threshold (μg L^{-1})**	**Ref.**	**OAV**				**TS**	**I**	**TS × I**
				HT-MW	**HT-WS**	**VCT-MW**	**VCT-WS**			
Ethyl octanoate	Apple. Fruity	5	[49]	**105.79 ± 7.33**	**110.61 ± 0.28**	**153.64 ± 9.01**	**137.63 ± 13.36**	*	ns	ns
Ethyl decanoate	Fruity, grape	200	[42]	0.13 ± 0.01	0.13 ± 0.00	0.19 ± 0.01	0.20 ± 0.01	**	ns	ns
Diethyl succinate	Light fruity, wine	6000	[42]	0.09 ± 0.00	0.20 ± 0.01	0.06 ± 0.00	0.04 ± 0.00	***	***	***
Acetate esters										
Isoamyl acetate	Banana	30	[38]	**75.68 ± 1.03**	**37.22 ± 0.61**	**181.23 ± 6.63**	**142.83 ± 12.21**	***	**	ns
Pheniethyl acetate	Banana, floral	250	[38]	**4.59 ± 0.07**	**2.93 ± 0.02**	**7.79 ± 0.13**	**4.47 ± 0.54**	***	***	*
Hexyl acetate	Green, floral	1500	[40]	0.02 ± 0.00	0.01 ± 0.00	0.07 ± 0.00	0.05 ± 0.01	***	*	ns
Fatty acids										
Butanoic acid	Sweaty	173	[51]	0.35 ± 0.04	0.48 ± 0.03	0.71 ± 0.05	0.74 ± 0.13	*	ns	ns
Propanoic acid	Butter, rancid	8100	[41]	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	ns	ns	ns
Isobutyric acid	Butter, cheese, rancid	2300	[40]	0.03 ± 0.00	0.03 ± 0.00	0.05 ± 0.00	0.05 ± 0.01	*	ns	ns
Hexanoic acid	Cheese, fatty	3000	[42]	0.41 ± 0.03	0.46 ± 0.01	0.72 ± 0.04	0.72 ± 0.02	***	ns	ns
Octanoic acid	Cheese, fatty, rancid	1000	[42]	**1.08 ± 0.01**	**1.16 ± 0.02**	**1.84 ± 0.09**	**1.63 ± 0.22**	**	ns	ns
cis-Geranic acid	Green	40	[52]	0.81 ± 0.09	**1.00 ± 0.06**	**1.06 ± 0.06**	0.70 ± 0.25	ns	ns	ns
trans-Geranic acid	Green	40	[52]	0.00 ± 0.00	0.01 ± 0.00	0.01 ± 0.00	0.01 ± 0.00	ns	ns	ns
Lactones										
γ-Butyrolactone	Toast, sweet, caramel	35.000	[53]	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	ns	ns	ns
Volatile phenols										
4-Vinylguaiacol	Clove, curry	40	[40]	**1.26 ± 0.13**	**1.31 ± 0.00**	**2.05 ± 0.02**	**1.84 ± 0.16**	**	ns	ns
4-Vinylphenol	Smoky, almond	180	[40]	0.11 ± 0.01	0.10 ± 0.02	0.19 ± 0.01	0.28 ± 0.03	**	ns	ns
Carbonyl compounds										
Acetoin	Lactic	10.000	[43]	0.01 ± 0.00	0.02 ± 0.00	0.01 ± 0.00	0.01 ± 0.00	*	*	*
Aldehydes										
Vanillin	Vanillin	200	[54]	0.00 ± 0.00	0.00 ± 0.00	0.01 ± 0.00	0.01 ± 0.00	ns	ns	ns

Values are means ± standard error of three samples. Significant differences for training system (TS), irrigation (I), and TS x I were analyzed by two-way ANOVA in a randomized block design (ns, not significant; *, p ≤ 0.05; **, p ≤ 0.01; ***, p ≤ 0.001). The bold numbers indicate OAV values higher than one.

In the present study, six terpenes (β-citronellol, nerol, geraniol, β-pinene, linalool, and terpilonene) and three norisoprenoids (α-ionone, β-ionone, and damascenone) were found, but terpinolene was only detected in wines from VCT-MW vines. The wines from vines trained in VC showed higher values for nerol and damascenone. However, geraniol had higher concentrations in wines from HT vines. The effect of irrigation had no clear effect on the concentration of these compounds in the obtained wines. However, as previously discussed, an interaction exists between irrigation and training systems in geraniol concentration. In this group of compounds, only two norisoprenoids (β-ionone and damascenone) were found to be above the detection threshold.

A total of eight ethyl esters were found in wines (ethyl butanoate, ethyl 2-methylbutyrate, ethyl hexanoate, ethyl lactate, ethyl isovalerate, ethyl octanoate, ethyl decanoate, and diethyl succinate) and detected in high amounts. The wines from VCT vines showed significantly higher concentrations of all ethyl esters, except ethyl 2-methylbutyrate, which showed no significant differences, and diethyl succinate, with higher concentrations in wines from HT vines. Irrigation treatment only had a significant effect on diethyl succinate, which also showed a significant interaction between the training system and irrigation. Thus, wines from HT-MW vines showed lower values of this compound than the wines from HT-WS vines, while in wines from VCT-MW vines, irrigation favored the concentration of diethyl succinate compared to wines from VCT-WS vines. Five of the total eight ethyl esters exceeded their detection threshold in all the wines analyzed.

Among the groups of acetate esters, three compounds were detected: isoamyl acetate, phenilethyl acetate, and hexyl acetate. Isoamyl acetate and phenilethyl acetate were detected in the wines at concentrations well above their odor threshold. On the contrary, hexyl acetate OAV was much lower than one. The concentration values showed similar trends between wines, with the highest values for wines from VCT-MW vines, followed by wines from VCT-WS, HT-MW, and HT-WS.

Seven fatty acids were detected in this study (butanoic acid, propanoic acid, isobutyric acid, hexanoic acid, octanoic acid, cis-geranic acid, and trans-geranic acid), but only octanoic acid showed a value above its odor threshold in all wines. Compound cis-geranic acid had an OAV value above one only in wines from HT-WS and VCT-MW vines. The training system had a clear effect on the concentration of fatty acids, with wines from VCT vines showing significantly higher values for five of the seven detected compounds. In contrast, the irrigation treatment had no significant effect on any of these compounds.

Only γ-butyrolactone was detected among lactones compounds, and it was present in concentrations below its odor threshold in all wines. The content of this compound was affected only by the training system, increasing the content in wines from VCT vines with respect to wines from HT vines.

Two volatile phenols were identified in this study: 4-vinilguaiacol and 4-vinilpehnol. The compound 4-vinilguaiacol was found at concentrations above the detection threshold in all wines. Wines from VCT vines showed higher concentrations of 4-vinilguaiacol and 4-vinilphenol than wines from HT vines.

Finally, all wines were found to contain one carbonyl compound (acetoin), and one aldehyde (vanillin). Acetoin was present in very low concentrations and showed significantly higher values for wines from HT vines. On the other hand, the concentration of vanillin was higher in wines from VCT vines compared to wines from HT vines. Both compounds showed very low OAV values.

3.7 Principal Component Analysis (PCA)

To better understand the effect of the treatments on the wine, a principal component analysis (PCA) was performed on the volatile compounds identified and quantified in Maturana Blanca wines, grouped by chemical families (Figure 3). The first principal component (PC1), which accounted for 62.3%, allowing to differentiate between VCT vines and HT vines. VCT vines, either under irrigation or non-irrigation, presented a general increase in wine volatile compounds compared with HT vines. HT-WS was positioned on the positive side of both principal components (PC1 and PC2) and was characterized by having high concentrations of carbonyl compounds and aldehydes. The group corresponding to the wines from HT-MW presented lower concentrations of all volatile compounds.

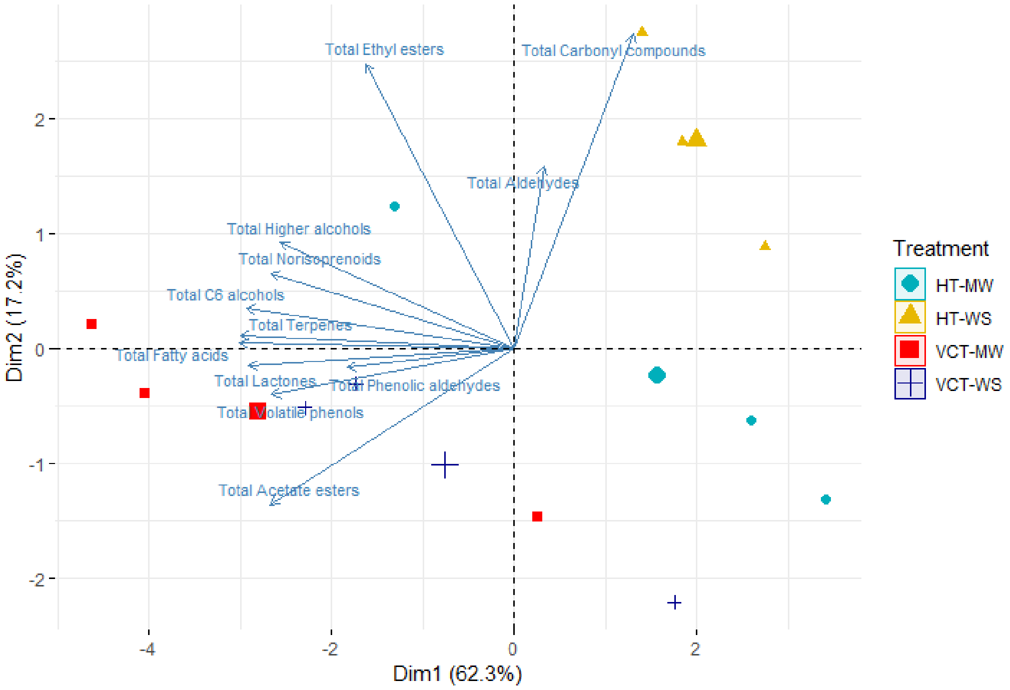

Figure 3. Principal component analysis (PCA) based on chemical families of volatile compounds determined in Maturana Blanca wines under different treatments.

4. DISCUSSION

Cultural practices can have lasting impacts on long-term grapevine productivity and may ensure vineyard sustainability [55]. The objectives of this trial were to assess the impact of vertical cordon trained (VCT) vines as an alternative to the traditional goblet training system (HT) to ensure a higher number of buds per vine in the cv. Maturana Blanca, which despite its high fertility, has the disadvantage of low production due to the small size of its clusters [12], and to include an in-depth analysis of training impacts on growing under different water status conditions, on vine performance and wine aroma compounds.

4.1 Vegetative Development

The effect of the training system on vegetative growth was higher than the effect of the irrigation treatment, thus indicating the high capacity of the training system to modify the vegetative response of vines [56].

In this study, a relatively stable pruning weight in WS and MW plants was observed in both training systems, indicating that the water deficit did not compromise vine capacity [57]. Contrarily, VCT allowed a greater number of retained spurs and, consequently, practically doubled the number of shoots per vine. Consistent with other reports [58], leaving more buds per vine resulted in a significantly larger leaf area, even with shoot length being inversely proportional to shoot number.

While total leaf area appeared to linearly respond to the number of shoots, being higher for VCT vines as compared with HT vines, pruning weight was similar for both training systems, independently of the increased number of shoots per vine. These findings are in line with other studies, which showed a compensation effect of the reduced number of shoots per vine with a larger shoot length and, consequently, larger shoot diameter (both parameters well correlated) [59], and a higher number of lateral shoots per vine, resulting in a very similar pruning weight. In the same line, Clingeleffer (1989) [60] showed that shoots that developed on minimally pruned vines were shorter and more closely noded than shoots on spur pruned vines.

A large number of training systems have been used to better match trellis systems to the vine vigor and to improve production efficiency by reducing canopy density, as well as increasing solar interception by the canopy surface and sunlight penetration into the canopy interior [61]. In this regard, VCT vines experienced a 1.5-fold increase in leaf area with respect to HT vines. Moreover, a higher percentage of leaf area in the HT treatment consisted of secondary shoots [62]. Although the increase in leaf area leads to an increase in the percentage of shaded leaves [63], the vertical distribution of the canopy of VCT vines makes the total leaf area very similar to the exposed leaf area [21]. In such a way, VCT may further manipulate the exposure of the leaf area to maximize the interception of light, leading to higher yield potential and to the optimization of the leaf area to fruit ratio.

4.2 Crop Yield

As expected, the training system had the greatest influence on plant yield, obtaining up to 1.8-fold increases in VCT plants with respect to HT vines and this was mainly because of the higher number of clusters per vine obtained in VCT plants as compared with HT vines. However, even with this large difference in the number of clusters per vine, the total weight per cluster was not influenced by the training system. In this case, berry weight in VCT vines was compensated by a higher number of berries per cluster as compared with HT vines, which resulted in a very similar cluster weight in both treatments. The differences in berry weight were mainly caused by lower water status in VCT vines, as observed by other authors [64]. Fruit set is described to be positively influenced by light penetration [65], and the high light penetration into the fruiting zone in VCT vines [21] may be the cause of the obtained higher number of berries per cluster.

On the other hand, irrigation led to higher yields in both training systems. This increase was greater in VCT vines, where the trend toward higher clusters per shoot, cluster weight and berry weight of VCT-MW vines lead to an increase in yield as compared with VCT-WS. The lower berry weight observed in vines subjected to water stress is in agreement with reports on Tempranillo [66], Cabernet Sauvignon [67], and Moscatel [68], where drought reduced berry weight.

It might be interesting to check if water stress affects bud fertility in later years. In this sense, some authors have found that irrigation favored higher fertility [17,66]. Moreover, the changes in the light microclimate within the renewal zone of the canopy due to the different training systems may influence bud fruitfulness the following season [69].

The greater increase in yield in VCT vines with respect to leaf area resulted in lower leaf area:yield ratios as compared with HT vines. Moreover, under both training systems, non-irrigated plants obtained higher ratios because of the reduction in yield. Similar effects were also reported in vines under different training systems [18], thus reflecting the greater efficiency of VCT vines compared to HT vines and MW plants compared to WS plants to ripen fruit per m^2 leaf area. Taking 1.0 to 1.5 m^2 leaf area/kg fruit as optimal values [70], our vines were above those values, suggesting that the cv. Maturana Blanca has an excessive vigor and that the employment of the VCT training system under moderate water stress conditions could result in more balanced vines.

It is interesting to note that this ratio did not affect the ripening of fruits, in contrast with several studies that reported that the reduction in leaf-to-fruit ratio resulted in a decrease in soluble solid accumulation [71–75].

The augmentation in yield led to a higher Ravaz index in VCT vines and WS plants. Generally, vines with Ravaz index values between 5 to 10 are considered in the optimal range [76,77]; however, for small-clustered vine varieties, such as cv. Maturana Blanca, the optimum values appear to be in a range from three to six [3]. Therefore, the values in HT vines (below 3.0) are indicative of excessive vigor, and the higher values obtained by VCT vines suggest a better balance between yield and vigor.

4.3 Must Composition

It is reported that freely directed training systems achieved well-exposed fruit zones with relatively low leaf area [18], and this may affect grape composition [78]. However, in this case, the sugar and titratable acid content suggested that the fruit maturation was similar among training systems and irrigation treatments. On average, the training system had more effect on the must composition components than the irrigation treatments. The concentration of malic acid was lower in the musts of VCT vines, which could be due to greater exposure of the clusters and, therefore, a greater degradation of this acid as a result of a higher temperature [79]. On the other hand, tartaric acid was affected by irrigation treatment but not by the training system. The reduction in the content of this acid in non-irrigated plants might be attributed to a dilution effect and, therefore, irrigation may affect the balance between malic and tartaric acid [80]. The relationship between these two organic acids may show the ability to retain acidity during ripening and suggest that cv. Maturana Blanca is an interesting option as a measure of adaptation to climate warming [81].

There was a linear relationship (r = 0.71, $p < 0.05$, n = 12) between potassium concentration and must pH (data not shown), which is consistent with some authors [82–84] but in contrast with another findings [85]. The lowest values of potassium and pH were observed in VCT vines, but both parameters were not affected by water deficit. The greater accumulation of K in HT vines may be due to a greater shading of the canopy, as has already been reported by other authors [86,87]. The higher values of pH observed in HT vines might be detrimental to the sanitary and aging stability of the wines.

The slight increase in the content of phenolic compounds in VCT vines is probably due, among other aspects, to differences in the source-sink ratio and the fruit-zone microclimate. In this sense, the training system may significantly influence the phenolic composition of the berries [88] and, thus, an increase in sun exposure can lead to an increase in the concentration of phenolic compounds, given their important role against UV radiation [89].

A clear detrimental effect of irrigation on must phenolic content was observed. This has also been previously reported in other studies [90] and may be explained in part by the lower berry size in non-irrigation vines. It is generally assumed that smaller berries have a higher surface:volume ratio and, therefore, a higher concentration of secondary metabolites in must [91].

4.4 Wine Aroma

Higher alcohols were quantitatively the major volatile compounds in all wines, indicating that these volatiles played a significant role in the determination of the overall aroma. Some of these compounds are related to herbaceous notes, whereas others are positive contributors to wine aroma, being characterized by floral and fruity aromas [13]. Amino acids can be metabolized into higher alcohols during winemaking, and therefore, the higher concentration of higher alcohols in VCT vines might be mainly due to differences in amino acid composition between training systems [92]. The high concentration of isopentanol and 2-phenylethanol was in agreement with the results shown by other authors for Maturana Blanca wines [13]. Both compounds are positive contributors to wine aroma and are characterized by banana notes [39] and floral aromas [38].

The C6 compounds, hexanols and hexenols, have a negative impact on the aroma of the wine, usually adding herbaceous and vegetal notes [93]. These compounds are derived from membrane lipids via the lipoxygenase pathway [94], and a high concentration is associated with a lack of grape maturity [95]. In our study, we found no significant differences in the maturation of the different treatments, but wines from VCT vines showed higher concentrations than wines from HT vines. Belancic et al. (1997) [96] reported a higher concentration of C6 alcohols in semi-shaded clusters compared to shaded and exposed clusters. In this sense, in our study, C6 alcohols increased their concentration in the clusters of VCT vines, which received higher sun exposure. The effect of irrigation is less clear, only 1-hexanol showed differences in terms of the interaction between the training system and irrigation. Thus, irrigation increased the concentration in wines from VCT vines but caused a decrease in wines from HT vines. The same trend was observed for the other C6 alcohols but without significant differences. Several studies have suggested that water stress increased the concentration of some C6 compounds [97,98], while other authors observed a decrease [99] or no effect on these compounds by water stress [100].

Terpenes and norisoprenoids in wine are mainly derived from grapes, possess floral and fruity nuances, and their composition in wine can indicate the varietal characteristics of wines [101]. Despite being found in very low concentrations; their low detection threshold means that these volatiles contribute significantly to the overall aroma of the wine [92]. Better exposure of the clusters on VCT vines led to higher concentrations of these compounds. Our results are in agreement with those found by Reynolds and Walder (1989) [102], who reported the highest concentrations of terpenes in partially shaded fruits, as sunlight exposure is a factor that promotes the biosynthesis of terpenes in the berries [103]. The increase in terpenes and norisoprenoids by better sun exposure was also reported by several authors through leaf removal treatments [104,105]. Although several authors reported the effect of a reduced crop on the increase in terpenes and norisoprenoids in wine [106,107], the better balance between vegetative and reproductive growth in VCT vines led to a higher concentration of these compounds. In these studies, different crop levels were obtained with cluster thinning, a practice that generally does not lead to changes in plant vigor. In general, drought increased terpenes in HT vines but caused a decrease in VCT vines. Some authors have shown that certain water stress favors the formation of terpenes in white aromatic cultivars [97,108]. In contrast, other authors have reported increases in terpene concentration in treatments that received higher water [95,109]. Certain water stress may favor the aromatic composition of wines, but severe water stress can negatively affect it [110]. The lower potential values reached by VCT vines compared to HT vines at ripening may explain this behavior.

Ethyl esters have a strong influence on wine aroma because they are normally found in high concentrations, and its OAV is usually low. These volatile compounds have normally been considered the primary source of fruity aromas and contribute to the wine aroma [111]. Within the group of acetate esters, the two compounds that showed concentrations above their detection threshold (isoamyl acetate and phenilethyl acetate) are characterized by banana aromas [44]. The high concentration of both compounds indicates that both are key molecules for the Maturana Blanca aroma [13]. The formation of esters can be affected by many factors such as yeast strain, fermentation temperature, oxygen availability and grape nutrient composition [112]. In our study, VCT treatment yielded a higher concentration of 9 out of 11 esters. These results are in accordance with other studies reporting that leaf removal and the consequent greater exposure to sunlight increase the concentration of esters in wine [113–115]. Šuklje et al. (2014) [114] hypothesized that higher UV radiation of clusters promotes the degradation of polyunsaturated fatty acids in grapes, as the compounds repress the genes involved in yeast activity and esters synthesis during fermentation. Moreover, the lower vigour of VCT vines may have contributed to the higher esters concentration, possibly due to higher nutrient density in the grapes [116], because of a better balance in terms of yield to shoot ratio [117]. Ethyl esters were barely affected by water status treatments but were affected by the interaction between irrigation and the training system. In our study, several esters increased in concentration in wines from VCT vines due to irrigation; however, the application of irrigation in HT vines led to a decrease in these same esters. These results are in agreement with the data shown by Talaverano et al. (2016) [98] for Tempranillo wines. These authors showed an increase in some esters in late regulated deficit irrigation, which coincides with the data of the present study.

Fatty acids can contribute to fatty, pungent, rancid, fruity, and cheesy notes to the overall aroma of the wine [118]. However, even being below their detection threshold, the fatty acids can contribute to the aromatic complexity of the wine; however, if their threshold is exceeded, the effects on aroma can be negative [92]. The influence of sun exposure and cluster microclimate on fatty acids concentration is discussed with some controversy in the literature. Previous reports claimed an increase in fatty acids with leaf removal [113,117], while others reported no effect [104,114], or even a decrease in fatty acids [89]. The greater number of buds in the VCT vines resulted in a higher concentration of fatty acids, which coincides with other reports that observed a tendency towards the increase in these compounds with higher crop levels [107,119]. Other studies reported changes in fatty acid composition in wines with different training systems [120]. In the present study, the fatty acid concentration was not affected by water status in vines, which is in agreement with other studies [98].

γ-Butyrolactone is the only lactone found in Maturana Blanca wines and is described as having toasted, sweet and caramel aromas [121]. Although differences were found between the treatments, its low OAV in all wines meant that it did not contribute to the final aroma of the wines.

Among the group of volatile phenols, only 4-vinylguaiacol and 4-vinylphenol were detected. Both compounds were found in the wines in similar concentrations to that described for other white wines [93], as vinylphenols are the main phenols in white wines [122]. These compounds can be responsible for spicy aromas, as well as heavy pharmaceutical odors [123]. The water status in vines showed no effect on the concentration of these compounds in wines

As expected in white wines, acetoin was present in very low concentrations. The content of this compound was affected by the training system and irrigation treatment, but due to its low OAV value, its contribution to the overall aroma of the wines can be considered null. However, acetoin is a precursor for the biosynthesis of 2,3-butanediol and diacetyl. The formation of 2,3-butanediol can contribute to the overall aromatic balance of the wine, whereas diacetyl is considered to be an organoleptic defect, particularly due to its characteristic odor and low perception threshold [124].

Overall, the effect of the training system on the aromatic compounds was higher than the effect produced by the water withholding on grapevines, both practices extensively studied by different researchers [125,126]. The obtained differences in the source-sink ratio, cluster microclimate, and berry size between both training systems may be the consequence of the higher concentration of volatile compounds in VCT vines as compared with HT vines. In this sense, obtaining an adequate balance between the reproductive and vegetative growth of the plants is fundamental to optimal fruit ripening [125] and, therefore, to obtain an adequate composition of volatile compounds [127,128]. For this reason, the best-balanced vines obtained within the VCT system led to a favorable effect on grape volatile composition. Moreover, the more exposed clusters in VCT vines might be another reason for the increased concentration of aroma molecules, as has been reported by other authors for different training systems [129,130], and for fruit-zone leaf removal [114,131]. Exposure to sunlight affects the microclimate of the clusters, affecting the composition of the must and the concentration of volatile compounds [132]. Etcherbarne, F., et al. (2015) [133] concluded that a reduction in berry size provided a greater aroma potential so that the lower berry size of the VCT treatments could further improve the aromatic content of these grapes.

The effect of irrigation on the volatile composition of the obtained wines was not as clear, although, in this case, an upward trend for irrigation treatments was obtained. Many authors have reported a higher aroma potential in vines under mild water deficit, while severe stress could reduce the volatile composition of grapes [110,134,135]. In this study, WS vines showed a severe water deficit during ripening, which could be the cause of the slight decreases in some volatile families of compounds. These findings show the importance of research for the implementation of balanced irrigation systems.

The result of the PCA showed the greater relevance of the training system on the concentration of volatile compounds in Maturana Blanca wines compared to the water regimes. Moreover, it can be noted that the water regime had greater effects on the concentration of volatile compounds in wines from HT vines than in wines from VCT vines. In this sense, wines from HT-WS vines had higher concentrations of carbonyl compounds and aldehydes compared to wines from HT-MW vines. Wines from VCT vines, positioned on the positive side of PC1, showed a tendency to increase the concentration of ethyl esters, higher alcohols, norisoprenoids, C6 alcohols, terpenes, fatty acids, lactones, volatile phenols, phenolic phenols and acetate esters. In this case, the PCA analysis could not differentiate between wines from VCT-MW vines and VCT-WS vines.

5. CONCLUSIONS

This study indicates that, with the appropriate training system, the yield could be increased with no detrimental impact on fruit quality and an increased aromatic profile in the cv. Maturana Blanca grown in the field under semi-arid conditions. This is because of the obtained differences in the source-sink ratios between VCT and HT vines, obtaining the VCT vines a better balance between vegetative and reproductive growth.

In both training systems, the application of irrigation also improved the relationship between vegetative and reproductive growth. These results indicate a greater efficiency of VCT and MW vines in ripening fruit and avoiding excessive vigor. Moreover, open canopies, such as the ones obtained in VCT vines, optimize yield and fruit composition, facilitate pruning, harvesting, spray penetration, and tend to have a more favorable microclimate. Nonetheless, we did not find differences in the ripening of the fruit or in most of the main compounds of the must, except for the lower values of potassium and pH obtained in the VCT vines. However, the secondary metabolism of the berries was affected by the different treatments. In white wines, the aroma plays a key role in the quality and typicity of the product , so enhancing the synthesis of these molecules through different approaches in the vineyard can also result in the improved aromatic intensity of wines. Indeed, from this study, it can be concluded that the training system and the amount of water applied may modify wine aroma quality. In this sense, future studies may have to optimize a good water status to enhance wine quality, by maintaining or slightly reducing yields, and improve the sustainability of water use. These data will provide the basis for adding value to cv. Maturana Blanca and favoring its use by Rioja winegrowers and wineries.

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