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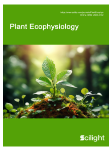

Article

Assessing Nutrient Dynamics in *Vitis vinifera* L. cv. Maturana Blanca: The Role of Training System and Irrigation Strategy

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Abstract: Global climate change presents significant challenges to viticulture, particularly regarding water availability and nutrient management. This study delves into the combined effects of vertical cordon (VC) and gobelet (G) training systems, alongside deficit irrigation (DI) and rainfed (R) regimes, on the physiology, nutrient dynamics, and productivity of *Vitis vinifera* L. cv. Maturana Blanca. The research uncovers that VC training increases vegetative growth and yield through enhanced light exposure and bud load, but careful nutrient management is required to address reduced phosphorus, iron, and zinc levels. DI effectively mitigates water stress, enhances intrinsic and instantaneous water use efficiency, and impacts nutrient uptake, notably increasing calcium and manganese levels while reducing nitrogen. Leaf blade and petiole analyses demonstrated complementary roles in understanding nutrient transport and physiological responses, with petioles reflecting short-term changes and leaf blades capturing long-term trends. The findings underscore the potential of combining VC training and DI to optimize vineyard resilience and productivity under climate stress while maintaining a balanced vegetative and reproductive growth ratio essential for high-quality grape production.

Keywords: grapevine; climate change; vertical cordon; leaf blade; petiole

1. Introduction

The wine sector faces escalating challenges, with climate change exacerbating issues such as increased temperature, altered precipitation patterns, and the pressing need for sustainable practices (Jones et al., 2005). The urgency of adaptation to maintain economically, socially, and environmentally sustainable viticulture is clear (van Leeuwen et al., 2024). Numerous techniques and adaptation strategies have been identified in viticulture (Gutiérrez-Gamboa, Zheng, & Martínez de Toda, 2020, 2021) and oenology (Dequin et al., 2017). It is also worth mentioning that a combination of different adaptation measures can be beneficial (Fraga, 2020). For example, the optimization of training systems and irrigation practices are fundamental, given their profound impact on vine health, yield, and fruit quality (Mirás-Avalos et al., 2017; de Rességuier et al., 2023a).

Researchers have developed numerous training systems to align vine vigor and improve production efficiency more effectively. These systems aim to decrease canopy density, increase its exposure to solar radiation, and enhance sunlight penetration into the interior (Smart & Robinson, 1991). Although little known, the vertical cordon (VC) is a freely directed training system used in some wine regions worldwide (Yuste, 2002). The vertical distribution of this system allows a more significant bud load per vine, resulting in a greater leaf surface area. Additionally, its vertical distribution provides a better canopy microclimate, maintaining a total leaf area similar to the external leaf area (Vanden Heuvel et al., 2004). Given that canopy structure influences water use and evapotranspiration, and considering that water resources for irrigation are expected to become scarcer in the future, understanding how training systems affect crop water needs and water use efficiency becomes essential (Fraga, García de Cortázar Atauri, & Santos, 2018).

Understanding how cultural practices interact with grape varieties and local soil and climatic conditions is crucial to unlocking the oenological potential (Van Leeuwen & Seguin, 2006). Although typical grape varieties are essential, particularly for Protected Designations of Origin (PDO) (Tscholl et al., 2024), the use of minority varieties can provide significant potential for adaptation to climate change (Morales-Castilla et al., 2020; Santos et al., 2020). In the Rioja PDO, the recovered cultivar Maturana Blanca was authorized in 2008 (Martínez De Toda, Balda, & Sancha, 2012) as a result of a project to recover, conserve, and study old genotypes that could represent valuable genetic combinations (Cervera et al., 1998; Martínez De Toda & Sancha, 1997). It is a vigorous and very fertile cultivar but not very productive due to the small size of its clusters. It is also quite rot-susceptible and is sensitive to sun damage (Balda & Martínez de Toda, 2017).

Both irrigation and training systems are practices that aim to enhance both crop production and quality, but they may also impact the plant's nutritional status by affecting nutrient availability, absorption, and distribution (Keller, 2005). Proper nutrient management is essential for maximizing the health and yield of grapevines. Vines need sufficient macro and micro-nutrients to support normal physiological and biochemical functions (Gilda-diana & Maria, 2017). Nutrient deficiencies or excesses can cause physiological disorders that negatively influence vine growth, grape yield, and wine quality. However, researchers have not yet fully established the nutritional requirements for producing high-quality crops. They need large data sets to define desirable nutrient ranges due to the variability in nutrient concentrations across different regions and grape variety-rootstock combinations (García-Escudero et al., 2013). Some researchers have suggested general sufficiency ranges based on adaptable data sets for various grape-growing scenarios (Proffit & Campbell-Clause, 2012). Nevertheless, the precision of these ranges decreases as other sources, such as seasonal weather variations, soil types, and vineyard management practices, introduce additional variability (García-Escudero et al., 2013).

Experts widely recognize plant tissue analysis as the most reliable method for determining grapevine nutritional status, with leaf blade and petiole analysis being the most commonly used practices (Christensen, 1984). Other complementary techniques, such as sap analysis, can help adjust nutrient applications by providing immediate results (Esteves et al., 2021). In European vineyards, growers use leaf blades as the standard tissue for nutrient diagnosis (Gärtel, 1996), while those in the United States and Australia prefer petioles (Robinson, 1992). A combined analysis of both tissues is recommended, as leaf blades offer reliability and petioles provide greater sensitivity (Benito et al., 2013).

This study aimed to evaluate the impact of the vertical cordon training system and deficit irrigation on the physiology, agronomic performance, and nutrient status of *Vitis vinifera* L. cv. Maturana Blanca. Additionally, knowing that researchers have described correlations between nutrient concentrations in plant tissues and plant development for several fruit crops (Mourão Filho, 2004), we sought to identify relationships between nutrient concentrations in leaf blades and petioles with key physiological, vegetative and productive parameters.

2. Materials and Methods

2.1. Location and experimental design

The research was conducted in a commercial vineyard of Maturana Blanca, grafted on R-110 rootstock, located in San Vicente de la Sonsierra, La Rioja, Spain (Latitude: 42°31′25″ N; Longitude: 2°43′23″ W; 466 m.a.s.l.) during the 2023 growing season. The vineyard was planted in 2015 with a row spacing of 2.40 m and a vine spacing of 1.30 m (3205 plants ha^{-1}).

We implemented a 2 × 2 factorial design to investigate the combined effects of two factors. The first factor, training system (TS), involved two free-standing training systems: the traditional gobelet (G), pruned to five spurs with 10 buds, and a vertical cordon (VC) system, with 10 spurs and 20 buds, as shown in Figure 1. The second factor, irrigation treatment (I), compared a rainfed treatment (R), where no additional irrigation was applied during the growing season, with deficit irrigation (DI), which supplied water at 30% of the reference evapotranspiration (ET$_0$). The ET$_0$ was calculated using the Penman-Monteith equation (Allen et al., 1998), and irrigation was applied every 10-12 days from July to September. A buffered row was established to ensure clear separation of the irrigated and non-irrigated plots. The R plots only received water from rainfall (a total of 474.2 mm during the season, with 244.4 mm during the growing season), while the DI plots received 76.6 mm of manual irrigation in addition to the rainfall.

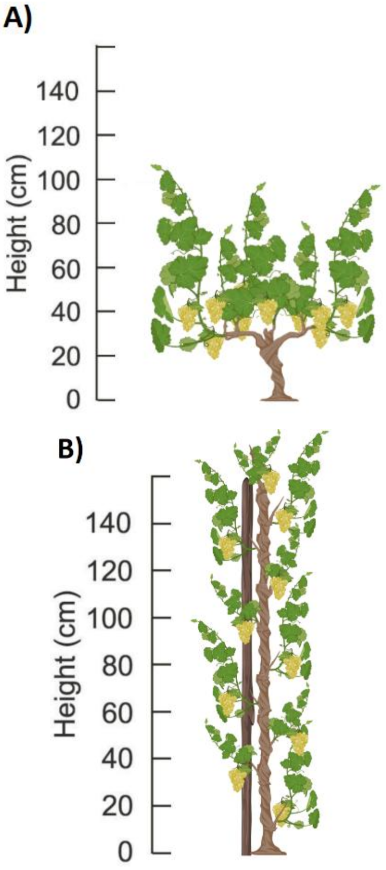

Figure 1. Schematic representation of the two different training systems: (**A**) Gobelet (G), and (**B**) Vertical cordon (VC).

The treatments were organized into the following four combinations: (i) rainfed gobelet (G-R), (ii) deficit irrigation gobelet (G-DI), (iii) rainfed vertical cordon (VC-R), and (iv) deficit irrigation vertical cordon (VC-DI). This study employed a randomized block design with three replicates per treatment, each containing six grapevines, making up a total of 12 replicated plots.

2.2. Environmental conditions

Soil samples were collected from the surface layer (0–30 cm) at sixty points in the study area. The soil samples were homogenized, sieved in the laboratory, and then dried at 40 °C for one week before being sent to the Regional Laboratory of the Government of La Rioja (La Grajera, Logroño, Spain) for analysis. The soil was classified as a Typic Calcixerept (Inceptisols) soil with a sandy loam texture (54% sand, 28% silt, and 18% clay), calcareous ($CaCO_3$ = 12.3%), with 6% of active lime and a pH-H_2O (1:5) of 8.0. The soil had a low organic matter content (1%) and a low salinity (0.14 $dS\cdot m^{-1}$) with a medium cation exchange capacity of 12.65 $cmol(+)\cdot kg^{-1}$. The major limitation of the soil, apart from the low potassium (K) levels (149.5 ppm), was the lack of Magnesium (Mg) (135.0 ppm) and its imbalance with K and Calcium (Ca). The rest of the macro and micronutrient levels were within the normal range, except for phosphorus (P), which was found to be high (41.5 ppm). No type of fertilization was applied during the study.

The climate in the area is Mediterranean continental semiarid, with an average temperature of 12.66 °C over the past 20 years, a reference evapotranspiration (ET_0) of 1108 mm, and annual rainfall of 541 mm, 39% of which occurs during the growing season. During the experimental season (from harvest to harvest), the accumulated rainfall was 474.2 mm, with 244.4 mm falling during the growing season. The seasonal reference evapotranspiration was 1194 mm, and the annual average temperature was 14.4 °C. Climatic data were obtained from the Agroclimatic Information Service of La Rioja (SIAR) near the vineyard.

2.3. Leaf gas exchange measurements and plant water status

Gas exchange and water status measurements were conducted simultaneously on the same days throughout the growing season, specifically on completely clear days between 11:00–12:00 solar hours, when photosynthetic active radiation (PAR) exceeded 1500 $\mu mol\cdot m^{-2}\cdot s^{-1}$. Healthy, fully expanded, and mature leaves exposed to sunlight were selected from the mid-upper region of the primary shoots, positioned both in the middle and outer parts of the canopy. In each replicated plot, measurements were taken from one leaf per plant on two representative vines, totaling six measurements per treatment. Gas exchange measurements were initially performed, followed by water status assessments on the same leaves at three key phenological stages: flowering, veraison, and ripening.

For the leaf gas exchange measurements, a portable infrared gas analyzer (Li-6400, LI-COR, Lincoln, NE, USA) was used to record stomatal conductance (g_s), photosynthesis (A_N), and transpiration rate (E). Intrinsic water use efficiency (WUE_i) was then calculated as the ratio of A_N to g_s, while instantaneous water use efficiency (WUE_{ins}) was calculated as the ratio of A_N to E. All measurements were conducted at ambient air temperature, under natural radiation conditions, and with a CO_2 concentration in the cuvette of 400 $\mu mol\cdot mol^{-1}$.

Vine water status was determined at midday by measuring leaf water potential (Ψ_{leaf}) using a pressure chamber (Soil Moisture Equipment, Corp., Santa Barbara, CA, USA).

2.4. Vegetative growth and yield components

During the veraison period, vegetative parameters, including total leaf area, were assessed on two representative vines per replicated plot, with six vines per treatment. The total leaf area (LA) was estimated using the non-destructive methodology described by (Sanchez-de-Miguel et al., 2010, 2011) and adjusted for the cv. Maturana Blanca (Puelles et al., 2022). Additionally, manual recordings of primary shoot length (PSL), number of primary leaves (PL), number of lateral shoots per primary shoot (LS), and number of leaves on lateral shoots (LL) were also conducted. The average internode length (IL) was calculated by dividing the shoot length by the number of leaves.

At the end of the growth cycle, the pruning weight (PW), number of spurs (NS), and the number of primary shoots (PS) were recorded for each vine, covering all six vines per replicate. The diameter of the second internode (SID) on five shoots from each of the six plants in each replicated plot was measured using an electronic digital caliper (Caliper DIN862, RS PRO, London, UK). For vines trained in the vertical cordon (VC) system, these measurements were extended to include both the top and bottom shoots of the cordon, with five measurements taken on each.

On September 7th, harvest operations were conducted manually, with all six vines per replicate being harvested (18 plants per treatment). During harvest, the number of clusters per vine (CV), the number of clusters per shoot (CS), the weight of each cluster (CW), and the overall yield (Y) (expressed in kg per vine) were meticulously recorded. Additionally, for a detailed assessment of berry weight, a random sample of 500 berries was collected from each replicate. The number of berries per cluster (BC) was calculated by dividing the weight of each cluster by the average berry weight. Moreover, for each of the six vines within a replicate, ratios were calculated for leaf area-to-yield (LA/Y), yield-to-pruning weight (Y/PW), and clusters per shoot, providing valuable insights into the efficiency and productivity of the vineyard management practices.

2.5. Leaf chemical analysis

For the plant mineral analysis, thirty healthy, fully developed leaves (five leaves from each of the six plants per plot) were collected at veraison from each replicated plot and treatment. Leaves were selected from fruiting shoots of medium vigor, positioned opposite to the second cluster (Romero, García-Escudero, & Martín, 2010).

Leaf blades and petioles were separated for independent analysis. They were washed three times with tap water, followed by a risen with distilled water, then dried in an oven (Dry-big, J.P. Selecta, Barcelona, Spain) at 70 °C for 48 h. After drying, the samples were crushed using an ultracentrifugal mill (ZM1, Retsch, Haan, Germany) and sieved with a 0.5 mm mesh.

To assess the total nitrogen content (N-organic + N-NH_4^+), 0.20 g of the ground material was analyzed via dry combustion using a Leco CNS analyzer (St. Joseph, MI, USA), applying the Dumas method (Etheridge, Pesti, & Foster, 1998). For other nutrients—phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), and boron (B)—0.20 g of each sample underwent wet digestion with H_2SO_4 (95%) and H_2O_2 (30%) (Hoenig et al., 1998) and were measured using inductively coupled plasma-optical emission spectrometry (Optima 3000DV, PerkinElmer, Norwalk, CT, USA). All dilutions were prepared with double deionized water (Milli-Q, Millipore, Bedford, MA, USA), and nutrient concentrations were calculated on a dry mass basis.

2.6. Statistical analysis

Data analysis was performed using RStudio software version 4.3.1 (RStudio: Integrated development for R., Boston, MA, USA). Heatmaps were made with R Studio (“ggplot2” package), the others with GraphPad Prism version 8.1.2 (Graph Pad Inc., San Diego, CA, USA). The normality and homoscedasticity were explored using the Shapiro-Wilk test (shapiro-test function) and Levene’s test (leveneTest function from “car” package), respectively. A two-way analysis of variance (ANOVA) was performed with a Generalised Linear Model (GLM) (lm function from “lme4” package) to examine statistical differences between training systems and irrigation regimes, as well as the corresponding interaction effects (Tables S1–S5). Physiological parameters were analyzed independently at each phenological stage by two-way ANOVA (lm function) (Table S3). The plot of normalized residuals vs. the fitted values was used to check the model’s assumptions. Outliers were initially eliminated before analysis (identify_outliers function from “rstatix” package (Kassambara, 2019)). Any statistical significance was accepted with a p-value < 0.05.

3. Results

3.1. Vine physiology across phenological stages

This study evaluated key physiological parameters, including leaf water potential (Ψ_{leaf}), net photosynthesis (A_N), stomatal conductance (g_s), transpiration rate (E), intrinsic and instantaneous water use efficiency (WUE_i and WUE_{ins}, respectively) across three critical phenological stages: flowering, veraison, and ripening (Table 1). We did not observe statistically significant differences between the treatments at flowering, except for the WUE_i value, which was higher in vines trained in vertical cordon (VC) (Table 1). During the veraison, deficit irrigation (DI) treatments exhibited less water stress, as indicated by a less negative Ψ_{leaf}. Our observations revealed no differences in Ψ_{leaf} between vines trained in gobelet (G) and VC. The application of irrigation significantly increased A_N and g_s, particularly in the G-DI treatment, which displayed the highest values for both variables (19.62 $\mu mol \cdot CO_2 \cdot m^{-2} \cdot s^{-1}$ and 0.295 mol $H_2O \cdot m^{-2} \cdot s^{-1}$, respectively). Likewise, A_N and g_s were significantly lower in vines trained in VC than in G-trained vines. Consequently, WUE_i was statistically lower in the DI treatments, with no differences between training systems. Transpiration rates were also higher in DI treatments, but TS did not affect this parameter. While WUE_{ins} was lower in VC-trained vines than those trained in G, irrigation increased WUE_{ins} in both training systems. A similar trend continued into the ripening phase, accentuating irrigation’s cumulative effects and changes in the training system (Table 1). Irrigation treatments consistently yielded more positive Ψ_{leaf} values, with no significant differences between training systems. Similarly, DI led to an increase in A_N and g_s compared to rainfed (R) conditions, although these values were lower than those observed at veraison, reflecting a natural decline as the vines matured. WUE_i values remained lower in DI treatments, but at this stage, G-trained vines had higher values than VC vines. It is worth noting the marked interaction between both factors (TS and I) which informs, for example, that the effect of irrigation on WUE_i is not the same in each training system. At this stage, E values were also higher in the DI treatments, as well as the G-trained vines. Finally, WUE_{ins} followed the same trend observed at veraison, with VC vines and rainfed treatments exhibiting significantly lower values.

3.2. Effects on vegetative parameters and yield components

The analysis of vegetative growth and yield components revealed notable differences between irrigation treatments and training systems (Tables 2 and 3), illustrating how these vineyard strategies impact vine growth and fruit production.

The training system significantly influenced vegetation growth metrics but not irrigation (Table 2). We found the most significant differences between both training systems in the number of shoots per vine (NS) and the number of primary shoots per vine (PS), in which the vines trained in VC practically doubled those G-trained vines. Consequently, the total leaf area (LA) increased by 25% in the VC compared to the G system. However, the rest of the parameters measured were lower in the VC vines. We found that the average length of the primary shoots (PSL) was 29.1% shorter in VC and reduced the internode length (IL). Consequently, we observed a reduction in the thickness of the shoot (measured as the diameter of the second internode (SID)) and the number of leaves per shoot (PL) in VC vines. In addition, the shoots of the VC developed 52.8% fewer secondary shoots (LS) and with a lower number of leaves (LL). Finally, we found no significant differences in the pruning weight (PW) between irrigation regimes or training systems.

Yield and its components varied significantly both with the application of irrigation and with the change of the training system, as can be observed in Table 3. Again, the more significant number of PS per vine in VC caused an increase in yield (Y) of 117.7% compared to the G system. This was mainly due to a 2.5-fold increase in the number of clusters per vine (CV) and a 24.5% increase in the number of clusters per shoot (CS). However, the training system did not significantly influence the parameters cluster weight (CW), berry weight (BW) and the number of berries per cluster (BC). The water regime also had a significant effect on yield components. Specifically, vines under DI exhibited higher Y, CV, CS, and CW values, with increases of 84.1%, 93.0%, 84.7%, and 36.3%, respectively. Although the irrigation factor did not significantly affect BW and BC, slight increases in both parameters under DI caused the aforementioned increase in CW.

Finally, we used two different indices to estimate the vine balance, and both were significantly affected by the two factors studied. On the one hand, the leaf area/yield ratio (LA/Y) significantly reduced its values in the vines trained in VC and the DI treatments, with excessively high values for the G-R treatment (7.35 $m^2 \cdot kg^{-1}$). On the other hand, the yield-to-pruning weight ratio (Y/PW) (known as the Ravaz index) showed the opposite trend, increasing in the VC and with the application of irrigation. Again, the G-R treatment showed values far removed from the rest of the treatments (0.96 $kg \cdot kg^{-1}$).

Table 1. Seasonal values of leaf water potential (Ψ_{leaf}, MPa), net photosynthesis (A_N, μmol $CO_2 \cdot m^{-2} \cdot s^{-1}$), stomatal conductance (g_s, mol $H_2O \cdot m^{-2} \cdot s^{-1}$), intrinsic water use efficiency (WUE_i, μmol $CO_2 \cdot mol^{-1}$ H_2O), transpiration rate (E, mmol $H_2O \cdot m^{-2} \cdot s^{-1}$), and instantaneous water use efficiency (WUE_{ins}, μmol $CO_2 \cdot mmol^{-1}$ H_2O).

Phenology		**Ψ_{md}**	**A_N**	**g_s**	**WUE_i**	**E**	**WUE_{ins}**
Flowering	G-R	−0.99 ± 0.02	12.30 ± 0.76	0.197 ± 0.009	63.41 ± 5.16	4.56 ± 0.12	2.71 ± 0.19
	G-DI	−0.94 ± 0.02	12.69 ± 0.39	0.204 ± 0.011	63.12 ± 3.47	4.72 ± 0.19	2.70 ± 0.11
	VC-R	−0.98 ± 0.03	15.02 ± 0.69	0.201 ± 0.009	74.79 ± 2.31	4.67 ± 0.18	3.22 ± 0.10
	VC-DI	−0.93 ± 0.03	12.20 ± 0.56	0.168 ± 0.012	73.98 ± 5.50	4.24 ± 0.19	2.89 ± 0.15
	TS	n.s.	n.s.	n.s.	*	n.s.	n.s.
	I	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
	TS × I	n.s.	*	n.s.	n.s.	n.s.	n.s.
Veraison	G-R	−1.54 ± 0.02	12.18 ± 2.30	0.126 ± 0.015	98.98 ± 4.68	4.00 ± 0.31	3.04 ± 0.07
	G-DI	−1.23 ± 0.02	19.62 ± 0.80	0.295 ± 0.013	66.71 ± 1.68	5.50 ± 0.16	3.57 ± 0.07
	VC-R	−1.58 ± 0.02	10.78 ± 1.01	0.107 ± 0.013	102.37 ± 3.48	3.91 ± 0.36	2.76 ± 0.05
	VC-DI	−1.23 ± 0.03	15.86 ± 0.41	0.216 ± 0.010	73.84 ± 2.13	5.38 ± 0.17	2.95 ± 0.05
	TS	n.s.	**	**	n.s.	n.s.	***
	I	***	***	***	***	***	***
	TS × I	n.s.	n.s.	*	n.s.	n.s.	*
Ripening	G-R	−1.63 ± 0.03	7.23 ± 1.03	0.062 ± 0.009	115.10 ± 3.34	1.83 ± 0.22	3.87 ± 0.15
	G-DI	−1.41 ± 0.04	13.87 ± 0.88	0.171 ± 0.012	81.63 ± 1.67	3.95 ± 0.25	3.52 ± 0.08
	VC-R	−1.63 ± 0.01	2.94 ± 0.82	0.034 ± 0.008	82.19 ± 6.42	1.16 ± 0.24	2.37 ± 0.23
	VC-DI	−1.37 ± 0.02	11.69 ± 0.86	0.136 ± 0.014	88.03 ± 4.61	2.88 ± 0.24	4.07 ± 0.06
	TS	n.s.	**	**	**	**	**
	I	***	***	***	**	***	***
	TS × I	n.s.	n.s.	n.s.	***	n.s.	***

Values are means ± standard error of six measurements per treatment. Significant differences for Training System (TS), Irrigation (I), and its interaction (TS × I) were analyzed with a general linear model (n.s., not significant; *, $p \leq 0.05$; **, $p \leq 0.01$; ***, $p \leq 0.001$).

Table 2. Mean values of several vegetative growth components of the different treatments. LA (leaf area, $m^2 \cdot vine^{-1}$), PSL (primary shoot length, cm), IL (internode length, cm), PL (primary leaves, $leaves \cdot shoot^{-1}$), LS (lateral shoots per primary shoot, lateral $shoots \cdot shoot^{-1}$), LL (lateral leaves per lateral shoot, $leaves \cdot shoot^{-1}$), PW (pruning weight, $kg \cdot vine^{-1}$), NS (number of spurs per vine, $spurs \cdot vine^{-1}$), PS (primary shoots per vine, $shoots \cdot vine^{-1}$) and SID (second internode diameter, mm).

	LA	**PSL**	**IL**	**PL**	**LS**	**LL**	**PW**	**NS**	**PS**	**SID**
G-R	4.16 ± 0.27	128.28 ± 7.63	4.76 ± 0.21	26.89 ± 0.90	9.72 ± 1.45	27.22 ± 5.30	0.527 ± 0.07	4.93 ± 0.12	9.82 ± 0.10	10.85 ± 0.24
G-DI	4.24 ± 0.33	132.56 ± 7.25	4.67 ± 0.16	28.28 ± 1.03	11.11 ± 1.38	28.56 ± 4.17	0.452 ± 0.03	5.00 ± 0.10	9.69 ± 0.24	10.62 ± 0.26
VC-R	5.23 ± 0.46	91.94 ± 5.06	4.16 ± 0.10	22.06 ± 0.99	4.94 ± 0.86	9.72 ± 2.39	0.495 ± 0.07	9.21 ± 0.33	19.63 ± 0.06	8.97 ± 0.17
VC-DI	5.27 ± 0.19	92.94 ± 6.56	3.94 ± 0.18	23.28 ± 0.84	4.89 ± 0.60	7.89 ± 1.23	0.447 ± 0.02	9.51 ± 0.15	18.83 ± 0.49	9.29 ± 0.16
TS	**	***	***	***	***	***	n.s.	***	***	***
I	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
TS × I	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.

Values are means ± standard error of six (LA, PSL, IL, PL, LT, and LL) or eighteen (PW, NS, PS, and SID) vines per treatment. Significant differences for Training System (TS), Irrigation (I), and its interaction (TS × I) were analyzed with a general linear model (n.s., not significant; **, $p \leq 0.01$; ***, $p \leq 0.001$).

Table 3. Yield and yield components of the different treatments. Y (yield, kg vine^{-1}), CV (clusters per vine, clusters·vine^{-1}), CS (clusters per shoot, clusters·shoot^{-1}), CW (cluster weight, g), BW (berry weight, g), BC (berries per cluster, berries·cluster^{-1}), LA/Y (leaf area: yield, m^2·kg^{-1}), Y/PW (yield: pruning weight, kg·kg^{-1}).

	Y	CV	CS	CW	BW	BC	LA/Y	Y/PW
G-R	0.57 ± 0.05	8.50 ± 0.50	0.87 ± 0.05	77.00 ± 4.55	1.21 ± 0.05	63.73 ± 2.13	7.35 ± 1.25	0.96 ± 0.04
G-DI	1.47 ± 0.24	14.60 ± 0.61	1.55 ± 0.06	99.95 ± 11.55	1.41 ± 0.04	70.57 ± 6.48	3.04 ± 0.50	3.35 ± 0.77
VC-R	1.78 ± 0.76	19.10 ± 2.50	0.97 ± 0.13	60.70 ± 4.22	1.15 ± 0.16	61.63 ± 9.95	3.78 ± 1.65	3.20 ± 0.78
VC-DI	2.85 ± 0.01	38.67 ± 0.82	1.95 ± 0.04	92.12 ± 2.33	1.26 ± 0.02	73.07 ± 2.51	1.85 ± 0.09	6.40 ± 0.31
TS	**	***	*	n.s.	n.s.	n.s.	*	**
I	*	***	***	**	n.s.	n.s.	**	**
TS × I	n.s.	**	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.

Values are means ± standard error of eighteen (Y, CV, CS, CW, BW, BC, and Y/PW) or six (LA/Y) vines per treatment. Significant differences for Training System (TS), Irrigation (I), and its interaction (TS × I) were analyzed with a general linear model (n.s., not significant; *, $p \leq 0.05$; **, $p \leq 0.01$; ***, $p \leq 0.001$).

3.3. Vine nutritional status

The mineral composition of leaf blades and petioles varied significantly across training systems and irrigation treatments, highlighting distinct nutrient uptake patterns and translocation, as illustrated in Figure 2. Specifically, the petioles showed more significant variability in response to the two factors studied than the leaf blades. In the leaf blades, the training system had a more pronounced effect than irrigation. Vines trained using the vertical cordon (VC) system exhibited notably lower concentrations of phosphorus (P), potassium (K), iron (Fe), and zinc (Zn), with reductions of 23.7%, 10.1%, 40.4%, and 23.1%, respectively (Figure 2A). DI led to a modest but statistically significant nitrogen (N) content reduction of 3.8%. Conversely, irrigation treatments had a more substantial impact in the petioles (Figure 2B). DI reduced the N content by 12.0% but increased calcium (Ca), P, and manganese (Mn) levels by 10.0%, 41.9%, and 38.9%, respectively. Similar to the leaf blades, the VC-trained vines showed significant reductions in P (18.1%), Fe (42.7%), and Zn (28.9%) concentrations in the petioles.

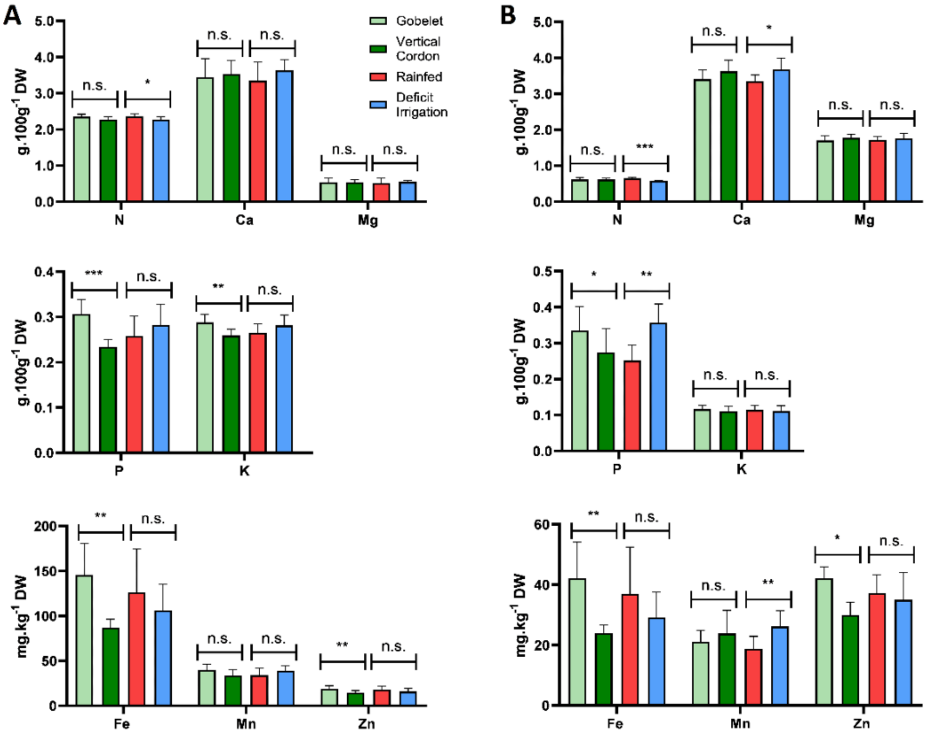

Figure 2. Nutrient concentrations in leaf blades (**A**) and petioles (**B**) at veraison for the factors training system (Gobelet and Vertical Cordon) and irrigation (Rainfed and Deficit Irrigation). Significant differences between training systems and irrigation regimes were analyzed by two-way ANOVA (n.s., not significant; *, $p \leq 0.05$; **, $p \leq 0.01$; ***, $p \leq 0.001$).

3.4. Relationship between nutritional status, physiological traits and agronomic performance

We could link the observed differences in nutrient concentrations to established correlations with physiological, vegetative, and productive parameters. Notably, the correlations involving nutrient concentrations in leaf blades showed different patterns than those found in petioles (Figure 3). The correlation with vegetative parameters in leaf blades was more substantial, revealing numerous statistically significant associations, especially for P, K, and Fe (Figure 3A). In addition, several agronomic parameters, including yield and berry weight, showed significant correlations, although to a lesser extent. However, we barely observed statistically significant correlations with physiological parameters.

In contrast, we found that nutrient concentrations in petioles were more strongly related to physiological parameters, especially for N, P, and Zn (Figure 3B), with the strongest correlations observed at veraison when collected lead samples for analysis. Although we also observed some correlations with yield parameters, they were less pronounced. Also noteworthy was the high correlation between the concentrations of Fe and Zn in petioles and vegetative parameters, but not for the other elements analyzed.

The correlations varied depending on the nutrient and the part of the leaf analyzed (Figure 3). We observed higher correlations in petioles for N, especially with physiological parameters measured at veraison. P showed strong correlations in both tissues but with different parameters: it correlated with vegetative development in leaf blades and plant physiology in petioles, particularly at veraison. K was highly correlated with vegetative parameters in leaf blades but showed no significant correlations in petioles. Fe and Zn showed fewer significant correlations, though they were primarily associated with vegetative parameters in both tissues, especially in the case of Zn in the petiole. In contrast, Ca, Mg, and Mn hardly showed any significant correlations, neither in the leaf blade nor the petiole.

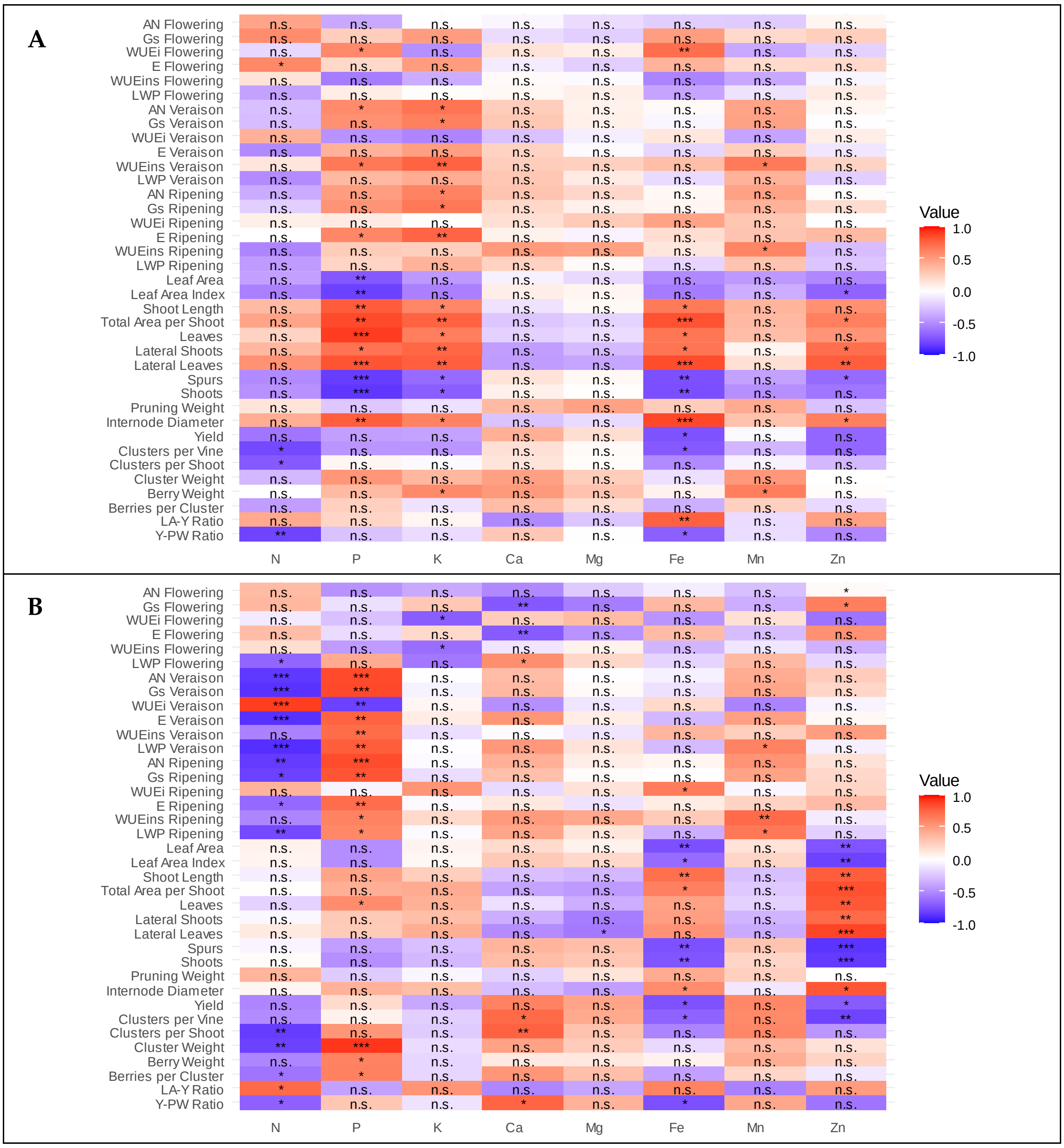

Figure 3. Heatmap of Pearson correlation coefficients between nutrient concentrations in the leaf blade (**A**) and petiole (**B**) with physiological, vegetative, and productive parameters. Figures were produced using R (v4.1.1., https://www.R-project.org (accessed on 15 July 2024)). The color scale shows the values of the Pearson correlation coefficient (positive values in red, negative in blue). The significance of correlations is shown (n.s., not significant; *, $p \leq 0.05$; **, $p \leq 0.01$; ***, $p \leq 0.001$). The abbreviations are as follows: AN, photosynthesis; Gs, stomatal conductance; WUEi, intrinsic water use efficiency; E, transpiration rate; WUEins, instantaneous water use efficiency; LWP, leaf water potential; LA-Y ratio, leaf area-to-yield ratio; Y-PW ratio, yield-to-pruning weight ratio.

4. Discussion

Different training systems represent an effective adaptation strategy to the decreased water availability. Traditional gobelet or bush vines, for instance, are known to mitigate excessive heating of grape clusters, preventing temperatures from rising far above ambient air levels and reducing the risk of sunburn (Gutiérrez-Gamboa, Zheng, & Martínez de Toda, 2020). Additionally, studies have shown that training systems with higher trunks increase minimum temperatures while reducing maximum temperatures in the fruit zone (de Rességuier et al., 2023b). However, there has been little discussion of the differential effects of these two free-standing training systems on water use efficiency and nutrient uptake. It is, therefore, essential to elucidate the effects of these training systems on water use efficiency and nutrient uptake to understand their field requirements better while mitigating the impact of heat waves.

At the flowering stage, the lack of significant differences among treatments suggests uniform environmental conditions and a late application of irrigation, which did not begin until after the fruit set. At this stage, all treatments experienced weak water stress (−0.9 to −1.1 MPa leaf water potential (Ψ_{leaf})) (van Leeuwen et al., 2009). During veraison and ripening, mostly irrigation played a key role in modulating plant responses to stress (Keller, 2005). While rainfed (R) vines showed severe stress (<−1.4 MPa Ψ_{leaf}), deficit irrigated (DI) vines showed moderate water deficit (−1.1 to −1.4 MPa Ψ_{leaf}) (van Leeuwen et al., 2009). These data demonstrate the effectiveness of DI in managing water use without severely stressing the vines (Chaves et al., 2007). Our observation of no differences in Ψ_{leaf} between vines trained using gobelet (G) and vertical cordon (VC) systems suggests that irrigation management may have overshadowed the influence of the training system on water status, which aligns with the findings from some authors (Valentini et al., 2022). However, other studies found higher water stress in those training systems that showed higher vegetative development (Mirás-Avalos et al., 2017; Puelles et al., 2022).

Net photosynthesis (A_N) and stomatal conductance (g_s) were higher in DI-treated vines, demonstrating that appropriate water management can significantly boost physiological activities, critical for fruit development and ripening (Pérez-Álvarez et al., 2021). However, g_s was only partly consistent with Ψ_{leaf}, as additional variables such as light, ambient CO_2, humidity, temperature, and wind influence stomatal closure (Kramer & Boyer, 1995). Nonetheless, g_s could be considered a better indicator of the intensity of water stress (Flexas et al., 2002; Mairata et al., 2024). In general, the g_s analysis indicated the absence of water stress ($g_s > 0.15$ mol $H_2O{\cdot}m^{-2}{\cdot}s^{-1}$), except in the rainfed treatments, where we detected moderate water stress at veraison ($0.05 < g_s < 0.15$ mol $H_2O{\cdot}m^{-2}{\cdot}s^{-1}$) and severe water stress at ripening ($g_s > 0.05$ mol $H_2O{\cdot}m^{-2}{\cdot}s^{-1}$) (Medrano et al., 2002). A_N and g_s were significantly lower in vines trained using the VC system than those trained in the G system. This observation initially suggests a lower physiological performance in VC-trained vines. However, we must carefully consider this interpretation in light of additional agronomic factors, particularly the leaf area. The VC training system potentially increases leaf area by up to 25% compared to the G system (Table 2) and greater sunlight interception (Vanden Heuvel et al., 2004). These increases can significantly affect the interpretation of physiological measurements such as A_N and g_s, which are usually expressed per unit area (µmol $CO_2{\cdot}m^{-2}{\cdot}s^{-1}$ and mol $H_2O{\cdot}m^{-2}{\cdot}s^{-1}$, respectively). Despite the inherent complexity in scaling physiological processes from the leaf to the canopy level, Escalona *et al.* (2016) concluded that the outer leaves in the eastern part of the canopy measured at midday were the most representative for estimating the whole-plant gas balance. Therefore, despite reduced g_s and A_N values, VC-trained vines showed increased leaf area (Table 2), which may compensate for lower per-unit-area physiological activity (J. M. Escalona et al., 2016). Transpiration rates (E) followed similar trends as A_N and g_s, with DI and G-trained vines showing higher values, particularly later in the cycle. Adjusting E values to account for increased leaf area in VC-trained vines suggests that overall plant transpiration may be comparable across training systems (L. Escalona, Flexas, & Medrano, 2000; Smart & Coombe, 1983).

Despite increased A_N and g_s, decreased intrinsic water use efficiency (WUE_i) in DI treatments highlights a fundamental trade-off in grapevine physiology. It is well known that WUE_i increases under water stress conditions, mainly due to stomatal behaviour (Schultz & Stoll, 2015). Stomatal closure is pivotal in modifying water use efficiency when vines experience water deficits. During drought, vines regulate stomata opening as a conservation strategy to optimize water usage. This regulatory process is governed by either hydraulic signals or hormonal responses, ensuring that water resources are preserved under stress conditions (Düring, 1988). Furthermore, as the season progressed, G-trained vines showed greater WUE_i, especially under rainfed conditions. The observed interactions between both factors (TS and I) show that each affects the other differently, suggesting, for example, that irrigation can optimize water use efficiency only in VC-trained vines. Although several authors use WUE_i as an indicator of water use efficiency (de Souza et al., 2005), instantaneous water use efficiency (WUE_{ins}) provides a more accurate measure of the carbon and water balance (Pou et al., 2012). Both parameters can frequently go in opposite directions (Schultz & Stoll, 2015). These same authors established a clear relationship between WUE_{ins} and leaf-to-air vapour pressure deficit (LAVPD), showing that WUE_{ins} often declines under water stress due to increased LAVPD, which intensifies stomatal limitations and reduces efficiency (Schultz & Stoll, 2015). Depending on the intensity of stomatal closure in response to water stress and how much LAVPD increases due to increased leaf temperature, these factors may reduce WUE_{inst}.

This study's WUE_{ins} values differed significantly between training systems, particularly under rainfed conditions. At veraison and ripening, vines trained in the G system consistently exhibited higher WUE_{ins} values than those trained in the VC system (Table 1). For example, at ripening, G-R showed a WUE_{ins} of 3.87 μmol CO_2 ·$mmol^{-1}$ H_2O, significantly higher than VC-R, which had the lowest value at 2.37 μmol CO_2·$mmol^{-1}$ H_2O. These data suggest that the gobelet system, with its compact canopy structure and lower vegetative growth (Table 2), may promote better instantaneous water use efficiency under water-limited conditions by reducing LAVPD and maintaining more favorable microclimatic conditions. Conversely, the VC system, characterized by a larger canopy and increased light penetration, might exacerbate LAVPD due to higher exposure of the leaf area to sunlight, potentially explaining the reduced WUE_{ins} values observed under rainfed conditions. However, under DI, the differences in WUE_{ins} between training systems were less pronounced, possibly indicating that water availability offsets the effects of increased evaporative demand in VC-trained vines. The data from this study are in agreement with other studies on grapevines (Koundouras et al., 2008; Naor & Bravdo, 2000; Schultz & Stoll, 2015), further highlighting the complex interactions between physiological responses, environmental factors, and training systems in determining WUE_{ins}.

Only the training system influenced vegetative growth, and we found no interactions between the training system and irrigation treatments. This finding suggests that the crop load did not affect the growth of the vines under deficit irrigation (Keller, Smithyman, & Mills, 2008). As expected, a more significant crop load resulted in a significantly larger leaf area (Keller et al., 2004). However, although VC vines produced twice as many shoots, their leaf area increased by only 25%. This fact was due to the compensatory effect of more shoots with shorter shoots, close nodes, and fewer leaves (both primary and secondary) (Clingeleffer, 1989; Miller, Howell, & Flore, 1996). Furthermore, the lower number of secondary shoots on VC vines (Table 2), combined with their vertical canopy distribution, made the total leaf area on VC very similar to the total exposed area (Vanden Heuvel et al., 2004). The compensatory effect of fewer shoots per vine in G vines, but with longer and thicker shoots and more lateral shoots, did not result in significant differences in pruning weight between treatments (Martinez De Toda, 2011).

Yield components varied significantly with the training system and the irrigation treatment, confirming that both factors are crucial in determining productivity. On the one hand, the higher yield in the VC was mainly due to a greater number of shoots and, therefore, a more significant number of clusters per vine, which is generally the primary determinant of production (Guilpart, Metay, & Gary, 2014). However, despite doubling the number of buds left per vine in the VC system, the number of clusters per vine increased by 2.5 times. This disparity resulted from a higher number of clusters per shoot, which was not a consequence of greater fertility but of more significant cluster desiccation in the G-trained vines. Shortly before the harvest, a heat wave with temperatures above 42 °C in late August caused sunburn necrosis, leading to shriveling of entire clusters. The damage was more severe in the G than in the VC, with 47.5% of bunches affected, compared to 34.7% in the VC system. The greater exposure of clusters in the VC from the early development stages (Vanden Heuvel et al., 2004) could favour an accumulation of photoprotectants, as observed in several studies with early defoliations (Brandt et al., 2019; J. Gambetta, Holzapfel, & Schmidtke, 2019; Verdenal et al., 2019).

On the other hand, the application of irrigation produced a greater yield per vine through an increase in most of the components analyzed. The heat wave influenced the notable differences in clusters per vine and clusters per shoot. Under water stress conditions, reduced canopy transpiration can cause an increase in fruit zone temperature, increasing the risk of sunburn (Tarara & Spayd, 2005). The higher cluster weight in DI treatments could be due to a lower incidence of berry desiccation (J. M. Gambetta et al., 2021), added to the upward trend in both berry weight and berries per cluster.

Achieving the right balance between vegetative and reproductive growth is one of the most important management issues in quality viticulture (Dry & Loveys, 1998). Our study showed significant differences in the indices used to estimate this balance. The leaf area-to-yield ratio (LA/Y), which ideally ranges between 1.0 and 1.5 $m^2·kg^{-1}$ (Keller, 2020), was closest to this range in the VC-DI treatment (1.85 $m^2·kg^{-1}$). The high vigor of cv. Maturana Blanca added to the low yield due to cluster desiccation, also characteristic of the cultivar (Balda & Martínez de Toda, 2017), which led to excessively high values in LA/Y. The VC system reduced this index, increasing yield potential and optimizing the leaf area/fruit ratio. Irrigation also caused a notable decrease, mainly due to production changes. Both factors reduced this ratio, suggesting they could result in better-balanced vines. The other index studied (Ravaz index) also showed values outside those considered optimal (from 5 to 10, Bravdo *et al.*, 1985), although for small-clustered varieties such as Maturana Blanca, the optimal values appear to be between 3 and 6 (Kliewer & Dokoozlian, 2005). The values indicated high vine vigor, especially for the G-R treatment, except for the VC-DI treatment. Again, both the VC and DI systems improved the values of this index.

The nutrient values measured in both leaf blade and petioles at veraison were broadly consistent with previously reported data for different cultivars and growing areas (Benito et al., 2013; Christensen, 1984; García-Escudero et al., 2013; Proffit & Campbell-Clause, 2012). However, manganese (Mn) and potassium (K) were notably lower than typically observed (Figure 2A). Soil alkalinity may have caused the Mn deficiency by affecting the bioavailability of certain nutrients, particularly Mn and iron (Fe) (Longbottom, 2009). Regarding K, several factors might contribute to its deficiency. Firstly, the soil's inherently low K concentrations (less than 150 ppm) can directly limit the amount of K available for vine uptake. Additionally, potential antagonistic interactions with calcium (Ca) and Mg can inhibit K absorption (Stockdale et al., 2013), as supported by a strong and negative correlation between Mg and K in petioles (r = −0.731, p = 0.007, N = 12). Finally, increasing water stress could prompt K early mobilization into the berries, further depleting the available K levels in grapevine foliage (Mpelasoka et al., 2003).

In this study, petioles exhibited more significant nutrient variability compared to the leaf blades, corroborating findings from other research (Fráguas, Miele, & Silva, 2003; Romero, García-Escudero, & Martín, 2013; Wolpert & Anderson, 2007). This sensitivity to environmental changes, such as irrigation, makes petioles reliable indicators for short-term nutrient status alterations (Davis, 1995). For instance, irrigation treatments notably influenced petiole composition (Figure 2B), likely due to its effects on hydraulic conductivity and vessel morphology (Dayer et al., 2017). Conversely, leaf blades maintain more stable nutrient concentrations, particularly for nitrogen (N) and K (Benito et al., 2013; Romero, García-Escudero, & Martín, 2013). This stability renders leaf blades more suitable for assessing the long-term effects of vineyard training systems on nutrient status over time. However, the lack of correlation between physiological parameters and nutrient content at phenological stages other than veraison suggests dynamic shifts in nutrient distribution and physiological responses throughout the season. At flowering, the virtual absence of significant correlations could be because different treatments did not yet clearly affect nutritional content and the physiological variables analyzed. During ripening, nutrient redistribution, environmental influences or mobilization of reserves could have contributed to the lower number of significant correlations observed. To further validate these findings, future research should incorporate multi-stage assessments to better capture nutrient dynamics across different growth stages.

The observed disparities in the nutrient content between leaf blades and petioles under different training systems and irrigation treatments reflect complex physiological mechanisms of nutrient uptake, translocation, and storage within the grapevine. The vertical cordon (VC) training system, which enhances canopy light penetration by reducing leaf layers, significantly impacts nutrient distribution (Vanden Heuvel et al., 2004). While this system promotes greater vegetative and reproductive development, it may also cause nutrient dilution or shifts in allocation favoring reproductive over vegetative growth (Mcgrath & Lobell, 2013; Puelles et al., 2022). The observed decreases in key minerals such as phosphorus (P), K, iron (Fe), and zinc (Zn) in VC-trained vines might reflect these redistribution strategies. Data presented in Tables 2 and 3 support these findings, highlighting the significant impact of training system modifications on vine growth and production. Conversely, the effect of deficit irrigation (DI) on petiole mineral composition underscores the role of water availability in nutrient transport (Plett et al., 2020). The increase in nutrients such as calcium (Ca), P, and manganese (Mn) in petioles under DI could be attributed to their enhanced solubility and absorption, facilitated by changes in soil moisture dynamics and root activity (Ippolito et al., 2019; Liu et al., 2017).

Contrary to previous studies, which reported a decrease in N content with reduced water availability (Spangenberg, Schweizer, & Zufferey, 2020; Torres et al., 2021), our results showed an opposite trend. In our study, N levels in leaf blades and petioles increased under rainfed conditions. This unexpected pattern may be explained by significant changes in source-sink relationships (Table 3), suggesting a possible relocation of N to the fruits. Further research is needed to determine whether this trend is consistent across different vineyard conditions and growing seasons. Finally, the numerous correlations observed between nutrient concentrations in leaf blades and petioles with physiological, vegetative, and productive parameters emphasize the complexity of plants as integrated systems, where multiple components interact with each other and with the environment (Tomkins, 2023). Correlation patterns between leaf blade and petiole analyses highlight their complementary roles in monitoring vine nutritional health (Benito et al., 2013). The stronger correlations between nutrient concentrations in leaf blades and vegetative parameters suggest that leaf blades may serve as reliable indicators of the overall nutrient status and vegetative growth (Christensen, 1984; Schreiner & Scagel, 2017). In contrast, petiole nutrient concentrations exhibited stronger associations with physiological parameters. These associations align with the understanding that petiole nutrient content reflects the plant's dynamic nutrient transport and real-time physiological processes (Shen et al., 2019).

Despite the known variability of N in petioles (Christensen, 1984), we found significant correlations with physiological parameters measured at veraison and ripening. The differential correlation patterns for P, which showed strong associations in both leaf blades and petioles but with different parameters, underline the dual role of P in supporting both growth and metabolic processes (Azeem et al., 2015; Duff, Sarath, & Plaxton, 1994). K is fundamental in stomatal function and water regulation (Zörb, Senbayram, & Peiter, 2014). However, we hardly correlated it with plant water status (Ψ_{leaf} or g_s), possibly due to its remarkably low content in both tissues analyzed. The correlations for micronutrients such as Fe and Zn, primarily with vegetative parameters across leaf blades and petioles, highlight their crucial roles in maintaining chlorophyll content and ensuring efficient photosynthetic activity (Keller, 2020). The pronounced association between Zn in petioles and vegetative growth could be particularly relevant for diagnosing micronutrient deficiencies that affect vine growth before visible symptoms appear. The minimal significant correlations observed for Ca, Mg, and Mn suggest that, despite their essential functions in plants (Rengel, Cakmak, & White, 2023), these elements may not vary distinctly enough with the measured parameters to serve as effective indicators of physiological, vegetative or productive status under the conditions studied.

5. Conclusions

Practices such as vertical cordon training and deficit irrigation have proven to be effective strategies for adapting vineyard management to the challenges posed by climate change (Gutiérrez-Gamboa, Zheng, & Martínez de Toda, 2020). These methods affect nutrient uptake and distribution, significantly impacting vine physiology, vegetative growth, and overall productivity. This study demonstrated that while the training system significantly influenced vegetative development and yield components, irrigation was key in managing grapevine physiological responses to environmental stress, particularly regarding water availability. The results suggest that integrating adapted training and irrigation strategies can significantly improve vineyard productivity and resilience to climatic variabilities. Furthermore, research on gas exchange responses within grapevine canopy illustrates how grapevines can adapt their physiological processes based on the timing and extent of regulated deficit irrigation. This adaptability is critical for understanding how deficit irrigation practices can optimize water use efficiency without compromising growth and productivity, especially in systems like VC, where increased exposure to light and air might otherwise increase water demand.

Variations in nutrient concentrations found in leaf blades and petioles suggest that the training system and irrigation regime differentially affect nutrient uptake and transport processes, necessitating appropriate management to avoid nutrient deficiencies and imbalances. For example, lower levels of key minerals (P, K, Fe) in CV-trained vineyards may require specific nutrient management practices to counteract potential deficiencies, especially in vineyards aiming for high-quality fruit production under conditions of reduced water scarcity.

Therefore, choosing between petioles or leaf blades for nutrient diagnosis hinges on the specific nutrients, the assessment's intended precision, and the vine's phenological stage. Leaf blade analysis provides a better indication of overall nutritional status and is more closely correlated to vegetative growth, while petiole analysis offers insights into real-time physiological processes, making it valuable for assessing immediate plant responses to environmental conditions. However, it is important to note that we only analyzed nutrient concentrations at veraison. Therefore, we should interpret these conclusions cautiously, as nutrient dynamics may vary at different phenological stages. Future studies should validate these findings by integrating multi-stage nutrient assessments throughout the vine cycle to develop more precise nutrient management strategies.

Supplementary Materials

The additional data and information can be downloaded at: https://www.sciltp.com/journals/PlantEcophys/2025/1/512/s1.

Author Contributions

M.P.: formal analysis, investigation, methodology, resources, writing—original draft; P.B.: conceptualization, resources; I.M.: investigation, methodology, resources; D.L.: investigation, methodology; A.M.: investigation, methodology; F.M.: supervision; A.P: funding acquisition, investigation, methodology, project administration, writing-review & editing. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement

The data is in the process of being uploaded to the National Digital Repository (CSIC) (https://digital.csic.es/). In the meantime, it is available upon request.

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Conflicts of Interest

The authors declare no competing interests.

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