

Article

Drought Adaptive Strategies in Mediterranean Grapevine Cultivars: Functional Trait Variability

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Abstract

Climatic changes in the Mediterranean area affect grapevine growth and productivity due to an increase in the magnitude and frequency of extreme climatic events. Functional traits of the vegetative stages of grapevines are drivers of stress tolerance, and their characterization may aid in the selection of cultivars showing greater resistance. Our aim was to evaluate and compare the adaptability to hot and arid climatic conditions of two varieties typical of small satellite islands of Sicily (Zibibbo and Corinto) with the two most common grape varieties grown on the main island (Catarratto and Nero d'Avola). The four selected varieties grew in a common rain-fed experimental germplasm repository. We followed seasonal changes in stomatal conductance, leaf water potential and leaf temperature, relating them to leaf water relation traits and xylem structural characteristics of the leaf vein network. We observed significant differences in functional traits and physiological behaviour of the four cultivars. Leaf water potential at turgor loss point was one of the most informative traits, together with midday leaf water potential and midday stomatal conductance. Nero d'Avola, Catarratto, and Zibibbo showed the highest adaptability to Mediterranean summer–autumn drought and heat stress through different physiological strategies; whereas, Corinto appeared more vulnerable. These findings highlight the importance of functional trait analysis for supporting cultivar selection, vineyard management, and future breeding strategies under climate change scenarios.

Keywords: climate resilience; drought tolerance; functional traits; grapevine physiology; hydraulic traits; Mediterranean viticulture

Academic Editor: Ziping Chen and Yi Han

Received: 16 June 2026

Revised: 31 July 2026

Accepted: 3 August 2026

Published: 9 August 2026

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1. Introduction

Grapevine (*Vitis* spp.) is one of the most economically important fruit crops cultivated worldwide, covering about 7 million hectares [1]. The domestication of vines occurred simultaneously about 11,000 years ago in western Asia and the Caucasus for the production of table and wine vines [2]. Cultivation and selection over many centuries under different climatic conditions has resulted in an enormous diversity of local grapevine cultivars (10,000–14,000). Natural and human selection have led to countless

typologies of wine, strictly related to a specific area of origin, and a multitude of table grape cultivars and rootstocks [3].

Climatic changes in the Mediterranean area affect grapevine growth and productivity due to an increase in the magnitude and frequency of extreme climatic events and to a greater variability in rainfall and temperature among years, with an expected increase in intensity and duration of drought and heatwaves in many regions [4–8]. Heatwaves pose a potential threat by determining a temporary decrease in net primary production and affecting carbon and water use in both natural and agricultural ecosystems [9,10]. Water availability is one of the most important environmental factors affecting crop growth and productivity. However, irrigation practices to overcome drought stress are not always sustainable [6], leading to the need to identify the already existing variability in grapevine varieties that are more resilient, better adapted to changing climatic conditions and may provide long-term sustainable solutions [11,12].

Functional traits of the vegetative stages of grapevines are drivers of stress tolerance and their characterization may aid in the selection of cultivars with greater resistance, as has been done across European vineyard regions [13]. Viticulture on the Mediterranean island of Sicily is one of the most important and ancient forms in Europe [14]. Native vines, many of which are known all over the world, have been cultivated on the island for many centuries [15]. The high number of autochthonous Sicilian grapevine varieties is an important source of genetic diversity, as the traits leading to adaptation under adverse environmental conditions may show significant intraspecific variation [16]. In field conditions, and particularly during summer months, plants are exposed to multiple stress factors, mainly heat, high solar radiation and soil water deficit [17].

Drought stress and high temperatures affect vine growth and productivity through a complex combination of physiological, hydraulic, morphological and phenological traits [18–21]. Water availability and high evaporation rates influence the regulation of stomatal closure and leaf water potential, which in turn affect gas exchange, growth and productivity. Leaf temperature is also influenced by stomatal conductance, and increasing temperatures affect biochemical photosynthetic processes. Stomatal closure is also linked to maintaining the functionality of the xylem network [20,22]. Leaf vasculature in turn plays crucial roles in water and sugar transport and mechanical support, and leaf vein architecture and density affect photosynthesis via hydraulic efficiency [23–26].

The capacity of grapevine cultivars to withstand prolonged water deficits is also related to their leaf-level hydraulic plasticity in response to water availability. Central to this are traits derived from pressure–volume (PV) curves, specifically the leaf water potential at turgor loss point (Ψ_{tlp}), osmotic potential at full turgor (π_0), bulk modulus of elasticity (ϵ_{max}) and leaf capacitance at full turgor (C_{ft}), that are considered as reliable indicators of drought stress tolerance [27]. The occurrence of seasonal osmoregulation and the maintenance of low osmotic potentials under drought conditions serve as a primary adaptive mechanism. By maintaining a lower Ψ_{tlp} , the vine can sustain a positive turgor pressure even as leaf water potential declines, thereby extending the window for gas exchange and carbon assimilation under stress. For grapevine, it has been proposed that osmotic adjustment is a pre-programmed seasonal strategy, largely independent of environmental variability [28] and that can therefore be expected to differ among varieties. Furthermore, the adaptive value of ϵ_{max} represents a strategic trade-off: higher values typical of stiffer cell walls allow for a rapid drop in leaf water potential, facilitating a steeper gradient for water extraction from drying soils, while more elastic walls help maintain turgor as leaf water content decreases. The elasticity of cell walls is causally related to C_{ft} , as it directly influences the amount of water that may be stored in the cells, with increased capacitance contributing to avoid desiccation and buffer changes in leaf water potential [29,30]. C_{ft} has been indeed considered as an important hydraulic trait for

wine grapes [31]. A comprehensive characterization of drought tolerance must integrate these multi-faceted traits to accurately predict grapevine varietal performance under fluctuating field conditions [20,32].

Trials conducted under natural conditions are necessary to characterize the integrated responses of grapevine varieties to multiple stress factors in the field [11]. The many Sicilian varieties have anatomical and physiological traits that allow them to resist different levels of drought stress and achieve different levels of productivity, as some of them have been selected to grow and produce under extreme conditions. Our aim was to evaluate and compare the drought and heat tolerance mechanisms of two varieties typical of small satellite islands of Sicily (Zibibbo and Corinto) to ascertain whether they show a greater adaptability to hot and arid climatic conditions than the two most common grape varieties grown on the main island (Catarratto and Nero d'Avola). Therefore, we examined the variability of some key functional traits in the four grapevine varieties grown in the same rain-fed vineyard. We measured in summer and autumn a set of traits commonly used to describe stress tolerance: stomatal conductance, leaf water potential and leaf temperature, relating them to leaf water relation traits (Ψ_{tlp} , π_0 , ε_{max} , C_{it}) and xylem structural characteristics of the leaf vein network.

2. Materials and Methods

2.1. Study Site and Plant Material

The study was conducted in an experimental vineyard within the perennial plant germplasm repository managed by the Institute of Biosciences and BioResources of the National Research Council of Italy (CNR-IBBR). This vineyard, which contains three replicates (plants) for each preserved grapevine accession, is located in the Collesano-Lascari district (Palermo, Italy 37°59'19.9" N, 13°54'55.8" E, 80 m a.s.l.) with a North-West exposure. The small size of the vineyard and the homogeneity of pedological and microclimatic conditions ensured that environmental variability was minimized, allowing differences in cultivar performance to be attributed primarily to genetic and physiological traits rather than spatial confounding factors. The soil of the experimental site is well drained, mainly represented by an association of regosols, brown soils and/or vertex brown soils, on clay. The vineyard was planted in 2006, and all cultivars were grafted on 1103 Paulsen rootstock. The collection is represented by 480 different clones/cultivars of domestic and wild vines, each accession/cultivar is represented by three cloned plants. The grapevines were in a planting pattern of 0.80 × 2.6 m and were vertically trained and pruned as simple guyot. Measurements were carried out on field-grown plants of four Sicilian cultivars of *Vitis vinifera* L., Nero d'Avola, Corinto, Catarratto and Zibibbo. Due to the conservation constraints and limited plant availability inherent to this national germplasm repository, data were collected from two adjacent cloned plants per cultivar. Measurements were taken in 2014 on three consecutive sunny days in summer (July, after berry set) and autumn (September, after berry ripening). Sampling days occurred after at least 15 days without precipitation according to the local meteorological station data.

The daily pattern of leaf water potential (Ψ_L) and stomatal conductance to water vapour (g_s) was followed from predawn to the afternoon.

Air temperature and relative humidity were recorded during measurements with a digital thermo-hygrometer (PCE-MHT 1, PCE Instruments, Southampton, UK). Photosynthetic photon flux density (PPFD) was recorded with a LI-250 Light Meter (LI-COR Biosciences, Lincoln, NE, USA) at leaf canopy level (Figure S1). The average air temperature data of the sampling dates were: in July T_{avg} 26.0 °C, T_{max} 36.1 °C; in September T_{avg} 24.2 °C, T_{max} 29.4 °C. Average monthly temperature and rainfall for the 10-year period 2014–2024 were calculated from data of the meteorological station of the SIAS

(Servizio Informativo Agrometeorologico Siciliano) closest to the experimental vineyard in Lascari (PA) (Figure 1).

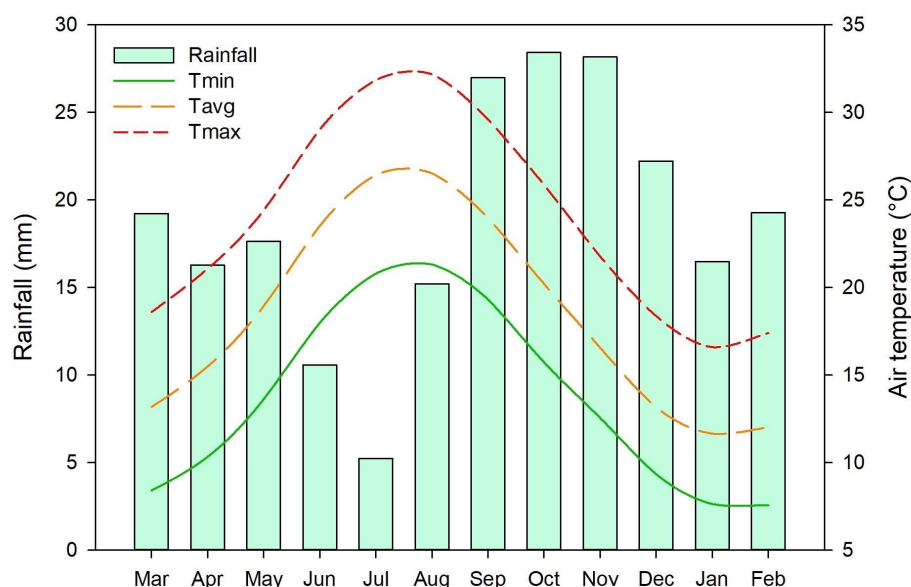


Figure 1. Average monthly air temperature and total monthly rainfall in the decade 2014–2024.

2.2. Pressure–Volume Curves

Five fully expanded leaves per cultivar collected from two individuals were used to construct PV curves by the bench dehydration method [33,34]; summer PV curves were constructed in July and autumn ones in September. Leaf petioles were cut under water and left to rehydrate in the dark for 2 h before starting PV construction. After correcting for oversaturation, when necessary, the PV curves were elaborated to obtain the main water relation traits related to drought tolerance: leaf Ψ_{tlp} , π_0 , ε_{max} and leaf area specific capacitance at full turgor (C_{it}).

2.3. Plant Water Status and Stomatal Conductance

To follow the daily pattern of Ψ_L , two fully expanded leaves per plant from two plants per cultivar were collected every two hours from predawn to 17:30 h, wrapped in cling film, stored in a cool-box and measured with a pressure chamber (PMS 1505D, PMS Instrument Company, Albany, OR, USA) within an hour. Between predawn and 17:30 h, abaxial g_s and leaf temperature (T_L) were measured every two hours with a porometer (SC-1 Leaf Porometer, Decagon, Pullman, WA, USA) on five south-facing, fully expanded leaves per plant. At the same time, independent T_L measurements were taken with a handheld infrared digital thermometer (All-Sun EM526, Eastern Technology Group, Zhangzhou, Fujian, China). In July, predawn sampling and measurements were carried out between 4:45 and 5:30, while in September between 5:30 and 6:15.

2.4. Leaf Mass per Area

Leaf mass per unit area (LMA) was calculated from six to nine leaves from two plants per cultivar, after removing the petiole. Leaf area (LA) was determined using the free software Image J (version 1.48v, National Institutes of Health, Bethesda, MD, <https://imagej.net>) to analyze the scanned images of the fresh leaves. Leaves were then oven dried at 70 °C for 72 h and dry weight was determined on an analytical balance. LMA was obtained by dividing leaf dry mass by LA.

2.5. Leaf Vein Density

Leaf vein classification followed conventional methods (e.g., [25,35]). The density of first, second and third order veins was determined on scans (MFC-L2700DN, Brother Industries, Ltd., Tokyo, Japan ~~Brother Int. Europe~~) of three fully expanded leaves collected from two plants per cultivar. For the determination of minor leaf vein density, portions taken from the middle part of three fully expanded leaves collected from two plants per cultivar were cleared by immersion in a 15% NaOH aqueous solution for 2 days in an oven at 35 °C. The cleared samples were then stained either with 1% (*w/v*) safranin O in 96% ethanol or with 0.5% (*v/v*) toluidine blue in phosphate buffer, pH 6.8. Images of the cleared and stained leaf samples were captured with a digital camera (Canon EOS 300D, Tokyo, Japan) attached to an optical microscope (Nikon HFX-DX, Nikon Corporation, Tokyo, Japan). Minor vein density (fourth- and higher-order veins) was determined at 4× magnification, from areas of approximately 1–2 mm² chosen between midvein and leaf margin. Image J was used to analyze the images. Total leaf vein density (Total VD) was calculated as the sum of major and minor vein density per unit leaf area.

2.6. Statistical Analysis

All data are presented as mean values ± standard deviation. The significance of differences among cultivars was tested by one-way ANOVA using the software package SigmaPlot 12 (Systat Software, Inc., San Jose, CA, USA). The normality assumption was checked using the Shapiro–Wilk test and equal variance with the Brown–Forsythe test. A level of significance of $p < 0.05$ was chosen to determine significant effects, followed by Duncan's Multiple Range test for pairwise multiple comparison when differences were significant.

Principal component analysis (PCA) of functional traits of each variety was carried out using the R package FactoMiner package (version 2.9) [36] and factoextra package (version 1.0.7 <https://CRAN.R-project.org/package=factoextra>, accessed on 23 January 2026).

3. Results

3.1. Pressure–Volume Curves

Results from the PV curve analysis are reported in Table 1. All cultivars showed osmoregulation between summer and autumn, with significant decreases in Ψ_{tp} and π_0 , while ε_{max} and C_{ft} did not vary significantly between seasons. Ψ_{tp} in summer ranged between −1.65 and −2.04 MPa, while in autumn it dropped to between −2.01 and −2.42 MPa, with Zibibbo reaching the most negative average values in both seasons, though this difference was not always significant (see Table 1). Correspondingly, Zibibbo had significantly greater concentration of solutes at full turgor, compared to the other cultivars. The ε_{max} in Nero d'Avola was similar to that of Corinto and significantly lower than in Cataratto and Zibibbo. C_{ft} was significantly higher in Zibibbo than in the other cultivars in autumn, while in summer Corinto and Cataratto had significantly lower C_{ft} average values.

Table 1. Leaf water relation parameters obtained by pressure–volume curve analysis of the four grapevine cultivars in summer and autumn. Leaf water potential at turgor loss point (Ψ_{tlp}), osmotic potential at full turgor (π_0), bulk modulus of elasticity (ϵ_{max}) and leaf specific capacitance at full turgor (C_{ft}) values are means of five replicates $\pm$ SD. For each season, means within columns followed by the same letter(s) were not significantly different according to Duncan’s Multiple Range test ($p < 0.05$). Averages in bold indicate significant differences between seasons within each cultivar.

Summer				
Cultivar	Ψ_{tlp} (MPa)	π_0 (MPa)	ϵ_{max} (MPa)	C_{ft} (mmol m ⁻² MPa ⁻¹)
Nero d’Avola	−1.68 $\pm$ 0.16 ac	−1.26 $\pm$ 0.05 a	12.3 $\pm$ 2.45 a	439.0 $\pm$ 32.6 b
Corinto	−1.65 $\pm$ 0.02 c	−1.30 $\pm$ 0.06 ab	17.3 $\pm$ 5.17 ab	242.7 $\pm$ 70.2 a
Catarratto	−1.89 $\pm$ 0.17 ab	−1.42 $\pm$ 0.11 b	22.2 $\pm$ 7.46 b	298.4 $\pm$ 75.7 a
Zibibbo	−2.04 $\pm$ 0.17 b	−1.60 $\pm$ 0.11 c	24.3 $\pm$ 5.28 b	473.0 $\pm$ 43.2 b
Autumn				
Cultivar	Ψ_{tlp} (MPa)	π_0 (MPa)	ϵ_{max} (MPa)	C_{ft} (mmol m ⁻² MPa ⁻¹)
Nero d’Avola	−2.01 $\pm$ 0.13 a	−1.45 $\pm$ 0.12 a	15.5 $\pm$ 1.68 a	394.0 $\pm$ 54.0 b
Corinto	−2.21 $\pm$ 0.11 ab	−1.65 $\pm$ 0.06 b	17.2 $\pm$ 1.65 a	301.0 $\pm$ 98.2 a
Catarratto	−2.29 $\pm$ 0.31 b	−1.65 $\pm$ 0.17 b	26.6 $\pm$ 6.34 b.	273.9 $\pm$ 84.7 a
Zibibbo	−2.42 $\pm$ 0.19 b	−1.94 $\pm$ 0.15 c	27.9 $\pm$ 4.92 b	506.1 $\pm$ 75.6 c

3.2. Leaf Water Potential

The daily pattern of Ψ_L in summer and autumn is shown in Figure 2. During summer, predawn leaf water potential (Ψ_{PD}) ranged between -0.15 and -0.75 MPa and Ψ_L decreased steeply in all cultivars after sunrise. Corinto showed significantly lower Ψ_L values both at predawn and in the late afternoon, when the other cultivars started recovering their leaf water status. Corinto was subject to stress for most of the day, as Ψ_L approached turgor loss point, while the other cultivars maintained Ψ_L values distinctly above their turgor loss point. In autumn, Ψ_{PD} values were lower for all cultivars, with Corinto showing a significantly lower value (-1.5 MPa) compared to the other three cultivars.

3.3. Leaf Stomatal Conductance

The daily pattern of g_s in the two sampling seasons is shown in Figure 3. As for the daily Ψ_L pattern, differences in leaf gas exchange were observed, depending on the cultivar and on the season. During the summer, air temperatures up to 36.1 °C were recorded during measurements; Nero d’Avola, Catarratto and Zibibbo showed similar patterns of g_s , while Corinto showed the lowest levels of g_s , 10 to 20 times lower than the other cultivars, opening stomata only for a few hours in the middle of the day. In autumn, Corinto showed extremely low levels of gas exchange. Catarratto had higher levels of stomatal conductance than the other cultivars in the central part of the day.

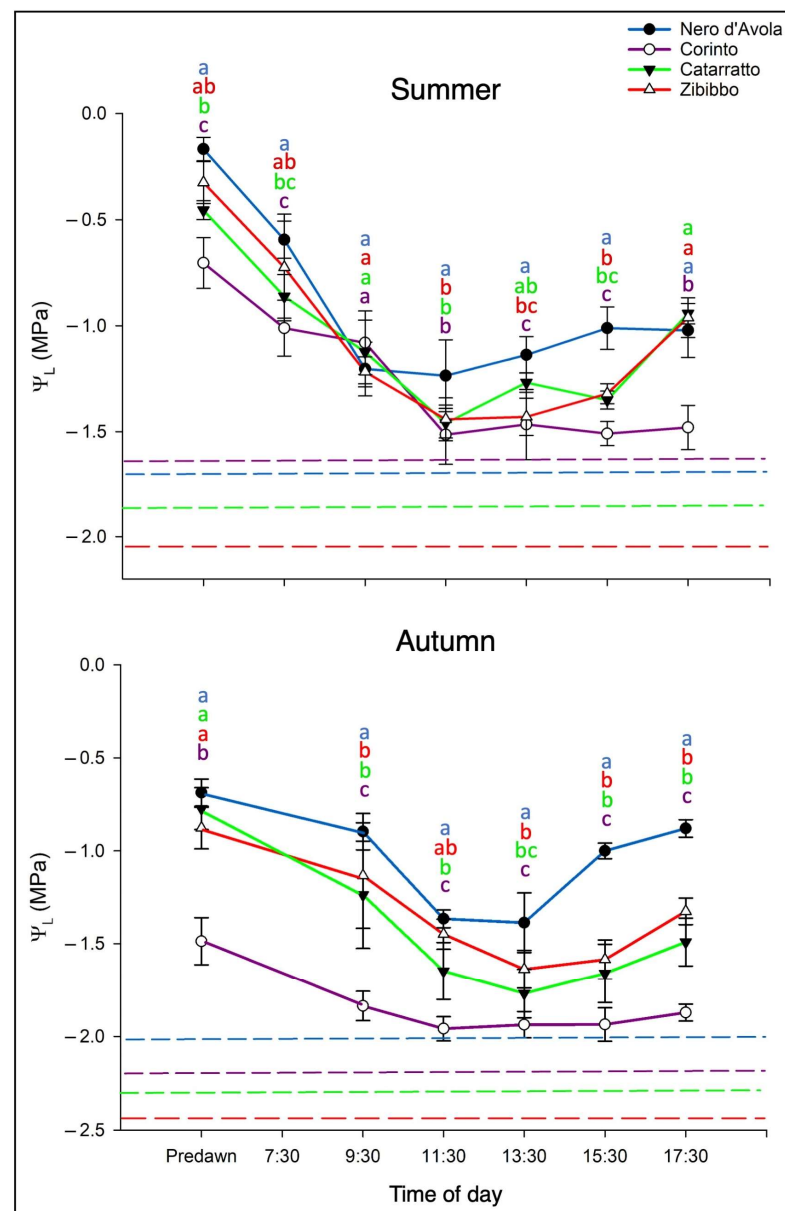


Figure 2. Daily pattern of leaf water potential (Ψ_L) measured in July and in September on the four cultivars, between predawn and 17:30 h. Data are presented as means $\pm$ SD. The dashed lines indicate the mean turgor loss point (Ψ_{tp}) values for the cultivars. Different letters indicate significant differences among cultivars within each sampling time ($p < 0.05$).

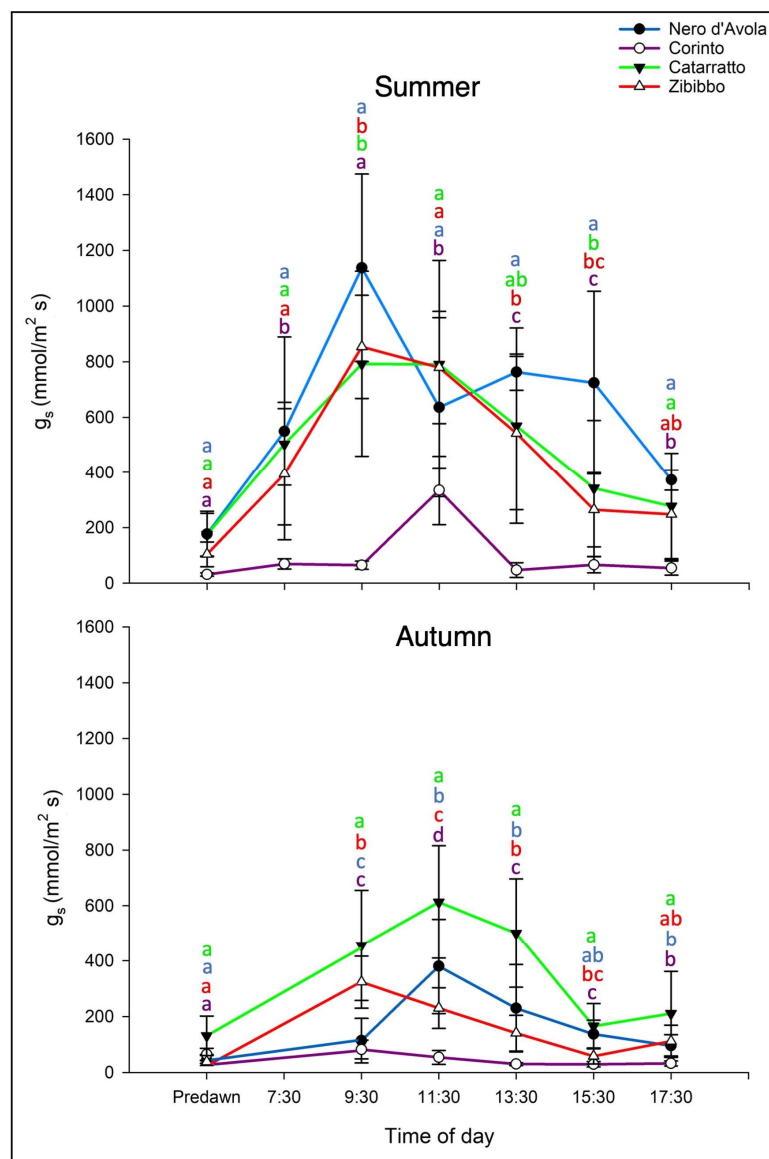


Figure 3. Daily pattern of leaf stomatal conductance to water vapour (g_s) measured in July and in September on the four cultivars, between predawn and 17:30 h. Data are presented as means $\pm$ SD. Different letters indicate significant differences among cultivars within each sampling time ($p < 0.05$).

3.4. Leaf Temperature

Independent measurements of T_l were recorded during measurement days (Figure 4). In summer, when the highest seasonal air temperatures were measured, Corinto was the cultivar reaching the highest leaf temperatures, 36.6 °C at midday. Nero d'Avola and Catarratto showed a similar pattern, reaching a maximum value of about 28.0 °C at 9:30 and maintaining this range of temperatures throughout the rest of the day. Zibibbo showed a slightly different pattern, with a slower increase in leaf temperature that peaked at 15:30 (30.0 °C) and decreased by about 4.0 °C within the next two hours. Though Corinto in autumn had the lowest levels of g_s compared to the other cultivars, leaf temperatures were in the same range of the other ones.

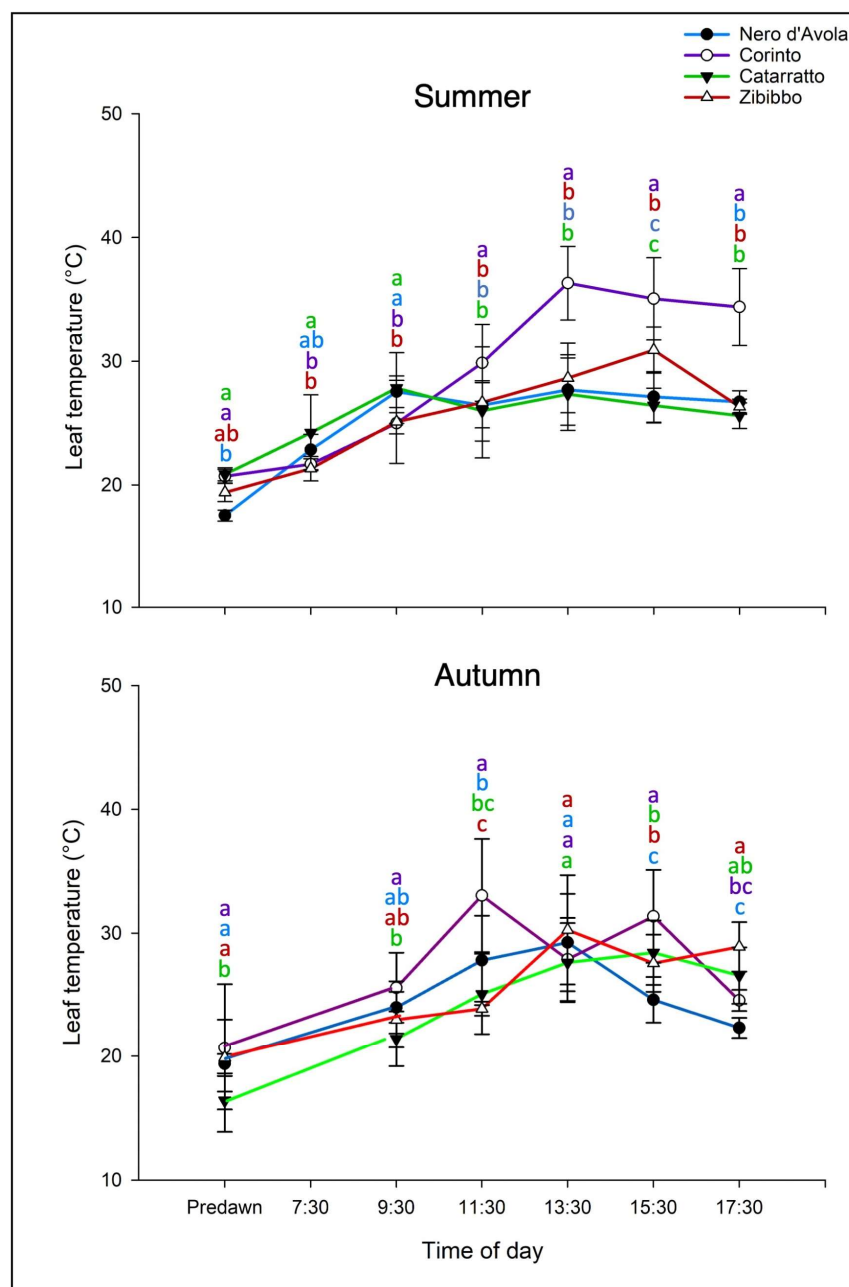


Figure 4. Daily pattern of leaf temperature measured in July and in September on the four cultivars, between predawn and 17:30 h. Data are presented as means $\pm$ SD. Different letters indicate significant differences among cultivars within each sampling time ($p < 0.05$).

3.5. Leaf Structural Properties

Examples of patterns of leaf vein density in the different cultivars are shown in Figure 5. Leaf structural properties, LMA and vein density (VD), of mature leaves collected in summer from the cultivars are reported in Table 2. The highest LMA value was found in Zibibbo, while the lowest in Catarratto. While no significant differences were found in minor VD among the cultivars, Catarratto showed a significantly higher density of major veins. The density of free ending veins was lowest in Corinto. Overall, total VD was significantly higher in Zibibbo compared to the other cultivars, followed by Catarratto, Nero d'Avola and Corinto (Table S1).

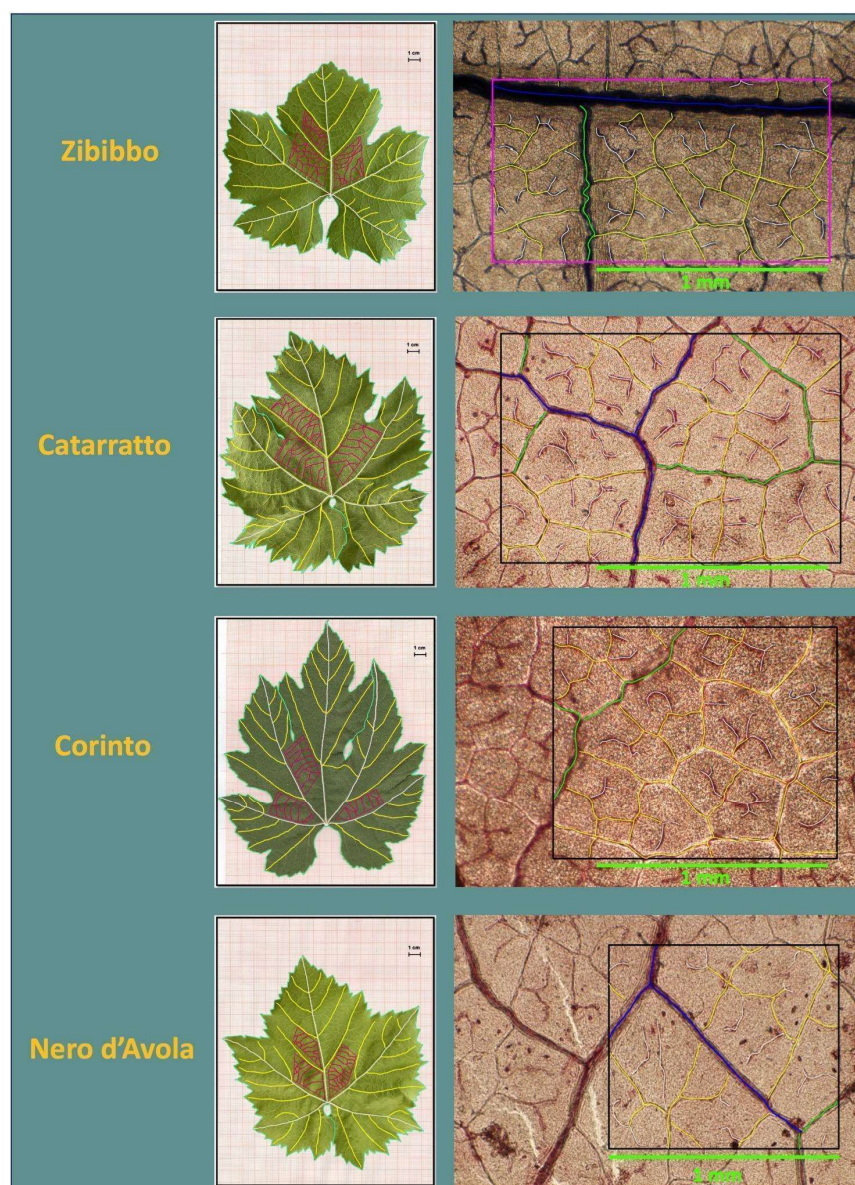


Figure 5. Images of the analysis of leaf vein density of major and minor veins of the four cultivars. The purple frames indicate the sampled leaf areas where vein measurements were performed.

Table 2. Leaf mass per unit area (LMA), density of major, minor and free ending veins of leaves of the four cultivars. Data are reported as means $\pm$ SD. For LMA $n = 5$, for vein density (VD) $n = 10$. Means within each column followed by the same letter(s) were not significantly different according to Duncan's Multiple Range test ($p < 0.05$).

Cultivar	LMA (mg cm^{-2})	Major Vein Density (cm^{-1})	Minor Vein Density (mm^{-1})	Free Ending Vein Density (mm^{-1})
Nero d'Avola	6.87 ± 0.34 bc	3.70 ± 0.13 a	9.19 ± 0.98 a	2.46 ± 0.34 ab
Corinto	6.06 ± 0.68 ab	3.52 ± 0.47 a	9.61 ± 0.83 a	2.05 ± 0.46 a
Catarratto	5.52 ± 0.89 a	4.74 ± 0.31 b	9.22 ± 0.95 a	2.72 ± 0.65 b
Zibibbo	7.47 ± 0.90 c	3.93 ± 0.47 a	9.75 ± 1.12 a	2.88 ± 0.45 b

3.6. Principal Component Analysis

All physiological and anatomical traits were included in the principal component analysis (PCA) (Figure 6) to assess their contribution to grapevine adaptive responses. The first two principal components explained 76.1% of the total variability observed among

the four varieties, revealing a clear differentiation of their functional traits. PC1 accounted for 46.7% of the total variance and primarily separated Corinto (COR) from the other varieties, being strongly associated with midday leaf temperature (TleafMD). PC2 explained an additional 29.4% of the variance and further discriminated the varieties. Along this axis, leaf mass per area (LMA) was mainly associated with Zibibbo (ZIB); whereas, midday leaf water potential (Ψ_{MD}) was associated with Nero d'Avola (NAV) and Catarratto (CAT), which clustered together and exhibited a similar physiological profile

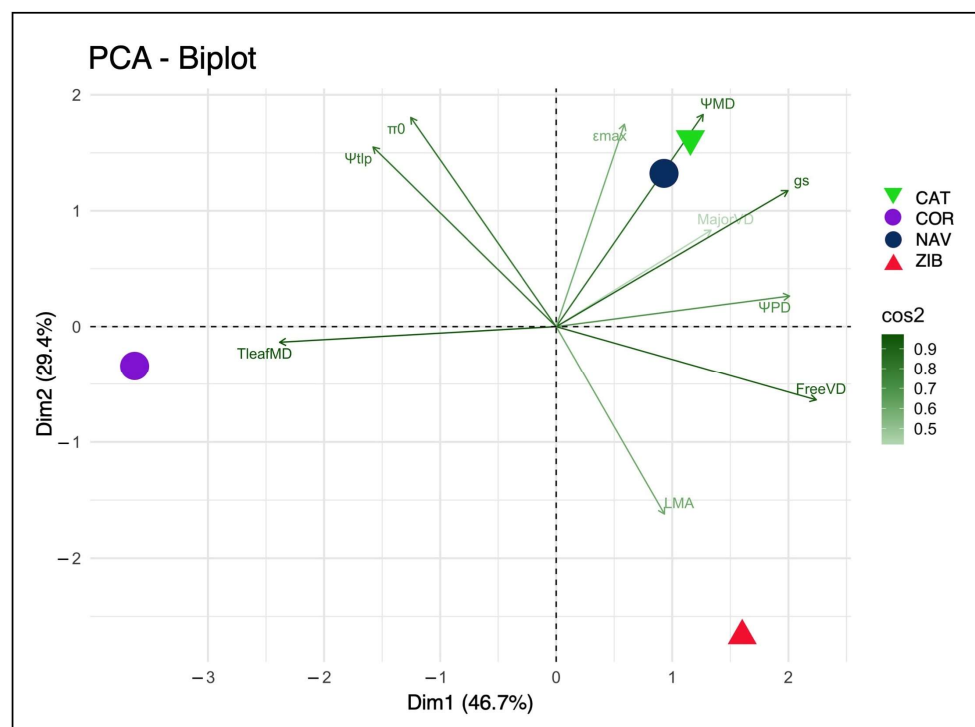


Figure 6. Principal component analysis (PCA) of functional traits in four grapevine cultivars grown under field conditions.

4. Discussion

We observed significant differences in functional traits and physiological behaviour of the four grapevine cultivars, two typical of the main island of Sicily (Catarratto and Nero d'Avola) and two typical of the circum-Sicilian islands (Zibibbo and Corinto). The study was carried out on a germplasm repository vineyard, therefore minimizing micro-environmental and localized soil spatial variability across the plot. Duplicate measurements were considered representative, since the collection comprised a total of three cloned plants per cultivar.

Grapevine has adapted to drought conditions through millennial cultivation [37], with differences in drought and heat response strategies among varieties and clones, due to adaptation to different geographical areas. Among the selected functional traits, those obtained from PV curves, such as Ψ_{TP} and π_0 , are reliable and widely used proxies of potential resistance to drought stress [6,38,39] and the association of low Ψ_{TP} with high drought tolerance has been widely reported (e.g., [27,40]). The regulation of water consumption by regulating g_s is also a useful trait to determine the adaptability of a genotype to limited water availability [41–43]. Based on Ψ_{TP} and π_0 , Catarratto was confirmed as potentially highly drought tolerant. Catarratto is one of the most important wine cultivars of Sicily where it has been cultivated for centuries [3] and is indeed highly appreciated for its resistance to drought and high temperatures. Catarratto was also able to avoid significant increases in T_L during the warmer hours of both summer and autumn sampling days.

This could be due both to relatively low LMA and high density of major veins. Anatomical and morphological traits, such as LMA and VD have often been related to the ability to cope with drought stress [34,44]. The high leaf VD of this cultivar is also in agreement with high levels of leaf hydraulic conductance measured in a previous study comparing well-watered and drought conditions [45], since higher VD is related to a smaller impact of hydraulic dysfunction in leaves [46].

Nero d'Avola, characterized by high Ψ_{tip} , π_0 and C_{ft} , showed a water spending strategy, with high levels of g_s throughout the day, at the same time maintaining Ψ_L above turgor loss point even under conditions of drought and heat stress. The maintenance of high g_s allowed for leaf cooling in the summer under high temperatures [47,48], making Nero d'Avola a well-suited genotype to face increasing temperatures and more frequent heatwaves. A possible explanation for the occurrence of limited decreases in Ψ_L under high transpiration could be the high C_{ft} we found for this cultivar [49]; C_{ft} is particularly important in defining hydraulic traits of wine grapes [31].

While root depth is a critical factor affecting water uptake [50], it was not directly measured in this study. However, because scion-rootstock interactions can significantly influence root system architecture and physiology [51–53], it remains possible that Nero d'Avola developed a deeper or more expansive root network despite being grafted onto the same rootstock as the other cultivars. This hypothesis is further supported by the less negative Ψ_{PD} values exhibited by Nero d'Avola, indicative of deeper root growth [50].

According to PCA, Cataratto and Nero d'Avola, both main island cultivars, were closely associated in their traits and strategy, strongly related to the maintenance of high g_s and high Ψ_{MD} .

Zibibbo showed the lowest Ψ_{tip} and π_0 , both in summer and autumn, so it could potentially be one of the most drought tolerant cultivars. The good level of recovery of Ψ_L in the summer afternoon may be explained by high VD of both major and free ending veins. Combined with high LMA, Zibibbo showed a tolerant strategy related to structural investment in leaf tissues. These findings are in line with the fact that this cultivar is widely grown in environments with extreme climatic conditions. Zibibbo was introduced in Pantelleria, a volcanic circum-Sicilian island characterized by a dry climate and strong winds, from Cape Zebib (Tunisia) during the Arab domination from the ninth to eleventh centuries [54].

Corinto separated distinctly from the other cultivars, as seen on the PCA biplot. It showed a water saving strategy with very low levels of g_s compared to the other three cultivars, particularly in summer. However, tight stomatal control did not avoid the drop in leaf water potential during the warmer hours of the day, and in summer the cultivar experienced relevant stress, as Ψ_L values approached Ψ_{tip} for several hours. Low leaf C_{ft} , low total and free ending VD of this cultivar could explain the lower recovery in Ψ_L during the afternoon in both sampling seasons. Stomatal closure also led to significantly higher T_L in summer. High leaf temperatures negatively affect carbon assimilation, reducing net primary production [55] and stomatal closure has been shown to result in cessation of berry growth in other grapevine varieties [56]. Corinto has indeed a quite low yield, with an average production of only 1 Kg/plant [57], while data available in Italian databases, show that Zibibbo has the highest yield, 4.6 Kg/plant, followed by Cataratto (3.6 Kg/plant) and Nero d'Avola (2.7 Kg/plant) (<https://vitisdb.it/>).

5. Conclusions

In our field conditions, Nero d'Avola, Cataratto and Zibibbo, through specific responses of each cultivar, responded best to summer conditions of drought and heat stress, while Corinto appeared to be the most sensitive. Data from this study confirm the variability in grapevine cultivars' response to aridity and high temperatures. Different morpho-

anatomical traits and different strategies adopted to regulate gas exchange and water status allowed adaptation to the Mediterranean environment. Leaf water potential at turgor loss point was one of the most informative traits, together with midday leaf water potential and midday stomatal conductance. Identifying such key functional indicators is particularly relevant in the context of ongoing climate change in Mediterranean viticultural areas, where increasing temperatures, prolonged drought periods, and more frequent heatwaves are expected to challenge grapevine productivity and sustainability. The identification of cultivar-specific adaptive strategies and key functional traits may support the development of more resilient viticultural systems through targeted cultivar selection and improved management practices. Moreover, the valorization of local grapevine biodiversity could represent an important resource for maintaining wine production under future climatic scenarios.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/horticulturae12080986/s1>, Figure S1: Average values of air temperature, relative humidity, and PPFD of the three sampling dates in each season. Table S1: Total vein density of leaves of the four cultivars. Data are reported as means $\pm$ SD, $n = 10$. Means followed by the same letter(s) were not significantly different according to Duncan's Multiple Range test ($p < 0.05$).

Author Contributions: L.A.: research design, experimentation, analysis, writing; S.I.: experimentation, analysis, writing; A.M.: experimentation, analysis; F.C.: research design, writing, review, editing, funding; M.S.: review, funding; A.N.: research design, review; E.O.: research design, experimentation, analysis, writing, review. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported in part by a PhD fellowship from the University of Palermo to SI (MIUR, XXV ciclo) and by Regione Siciliana (PSR Sicilia 2007–2013, Sottomisura 214/2A—Preservazione della biodiversità: Centri pubblici di conservazione, Grant No. 94750767637).

Data Availability Statement: The dataset is available on request from the authors without specific restrictions.

Acknowledgments: We thank Leonardo Pollina for microscopy work and image analysis of vein density.

Conflicts of Interest: Authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

C_{it}	Leaf specific capacitance at full turgor
g_s	Stomatal conductance to water vapour
LA	Leaf area
LMA	Leaf mass per unit area
PCA	Principal component analysis
PPFD	Photosynthetic photon flux density
PV	Pressure–volume
T_{avg}	Temperature average
T_L	Leaf temperature
T_{max}	Maximum Temperature
VD	Vein density
ϵ_{max}	Bulk modulus of elasticity
π_0	Osmotic potential at full turgor
Ψ_L	Leaf water potential
Ψ_{MD}	Midday leaf water potential

Ψ_{PD}	Predawn leaf water potential
Ψ_{tlp}	Turgor loss point

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