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ORIGINAL RESEARCH ARTICLE

Improved berry and wine quality of *Vitis vinifera* L. cv. Gewürztraminer grown in an arid climate using a Y-shaped training system

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ABSTRACT

Recent global climatic changes have highlighted viticulture in arid/semiarid regions as an increasingly relevant study model. Grapes in arid regions face excessive solar irradiance, leading to more than 50 °C berry surface temperatures in exposed berries. The resultant oxidative stress, sunburn necrosis, and browning consistently reduce berry quality. Adapting an adequate training system to the climate and cultivar is a simple and inexpensive method to control the radiation regime. This study compares the berry and wine characteristics and compositional components of desert-grown *Vitis vinifera* L. cv. Gewürztraminer, trained on either a Vertical Shoot Positioning (VSP) system or a Y-shaped training system (SAYM, Sistema di Allevamendo ad Ypsilon Integralmente Meccanizzabile), a method with a higher canopy light interception. The SAYM training reduced direct radiation and concomitant heat in the cluster zone and significantly alleviated oxidative stress in berries in the 2016/17 season. In addition, SAYM-grown berries were preferable in terms of quality and productivity. Correspondingly, a sensorial analysis rated SAYM wines higher than VSP wines in all categories. Photosynthetic pigment content in the berries' skin showed similarities between VSP and SAYM, and a volatile compound analysis of the wines by GC-MS revealed a higher ester content in the wines derived from SAYM vines, along with a higher content of compounds linked to Gewürztraminer wine typicity (varietal characteristics such as esters, terpenoids, and alcohols).

KEYWORDS: SAYM, arid viticulture, training system, volatile organic compounds, reactive oxygen species

INTRODUCTION

Most agricultural regions have been subjected to warming trends in recent decades, as noted in the 2019 Intergovernmental Panel on Climate Change (IPCC) (Shukla *et al*., 2020), making desert viticulture an increasingly relevant study model to understand grapevine acclimation and metabolic plasticity under high temperatures and solar irradiance. These conditions can cause berry sunburn and desiccation (Gambetta *et al*., 2021; Hulands *et al*., 2014; Krasnow *et al*., 2010) and an overall reduction in berry size and quality (Hulands *et al*., 2014), as well as higher sugar content. These factors may result in high alcohol percentages in wines (Laget *et al*., 2008; Rösti *et al*., 2018), high berry pH (Laget *et al*., 2008; Martínez-Pérez *et al*., 2020), and a reduction in malic acid, which leads to decreased berry titratable acidity (Laget *et al*., 2008; Spayd *et al*., 2002; Sweetman *et al*., 2014). In addition, a combination of high solar irradiance and temperature often exerts oxidative stress (Carvalho *et al*., 2015; Foyer *et al*., 1994; Mansour *et al*., 2022), a physiological condition resulting in an imbalance between the concentrations of antioxidants and reactive oxygen species (ROS) (Gashu *et al*., 2022). Excessive ROS accumulation may lead to cellular injuries and degradation of the metabolites that determine the wine quality and composition. Among the *Vitis vinifera* cultivars, white berries are more susceptible to radiation damage than red berries, as they lack antioxidant anthocyanins, photo-protective pigments against UV radiation, and high temperatures (Adams, 2006; Gashu *et al*., 2022). While red varieties are also sensitive to sunburn, the symptoms are not as apparent as in white varieties (Gambetta *et al*., 2021).

However, other antioxidant metabolite classes, namely carotenoids and polyphenols, have been proposed to protect white and red berries against sun and heat damage (Gashu *et al*., 2022). Abiotic stress triggers a complex system of responses, including secondary metabolites and antioxidants, which are not limited to ascorbic acid and occur regardless of berry skin colour (Yeshi *et al*., 2022). The prominent role carotenoids play in plants is the photoprotection of chlorophyll and the photosynthetic complex (Sun *et al*., 2022). They are considered to be a significant line of defence in plants against oxidative stress because of their capacity to quench ROS through a physical mechanism involving a transfer of excitation energy followed by thermal deactivation or by a chemical mechanism that involves their oxidation (Carvalho *et al*., 2015; Ramel *et al*., 2012; Sun *et al*., 2022). Carotenoid biosynthesis is induced by high light exposure and induced degradation by higher temperatures during the pre-veraison stages (Joubert *et al*., 2016; Mendes-Pinto, 2009; Young *et al*., 2016). Therefore, there appears to be a fine balance between the enhancing and the degrading effects of sunlight exposure and heat on carotenoids, which are also considered to be essential quality determinants and precursors of the low-threshold aroma compounds, C13-norisoprenoids (Mendes-Pinto, 2009).

Metabolic alterations, among other factors, in response to increasing temperature and increased radiation can significantly affect wine typicity (varietal characteristics). In a review by Drappier *et al*. (2019) on temperature effects on wine composition and typicity, climatic conditions substantially influence typicity more than other environmental factors. Additionally, the authors mention a shift in Bordeaux wine typicity under hot temperatures, illustrated by cooked fruit notes, higher tropical notes for white varieties, and changes in red wine colours (Drappier *et al*., 2019). In other regions, Gewürztraminer grapes and other white cultivars grown under high temperatures had a reduced aromatic expression compared to those grown in cooler conditions (Cataldo *et al*., 2021a; Ferretti, 2021).

One of the most essential aspects of grapevine cultivation is the training system applied in the vineyard. The training system can significantly impact the quality and productivity of the grapes produced (Gambetta *et al*., 2021). Training systems, including adjustments of the vine frame, are viticultural practices to alter the percentages of high-light-exposed leaves, microclimatic conditions in the cluster



FIGURE 1. (a) An illustration of the training systems in an in-row perspective: SAYM (left) and VSP (right). (b) Photos of the SAYM training systems: an open system (left) and the closing of the "Y" structure after harvest, to be opened again before the next season's bud burst (right).

zone, and total leaf area (de Rességuier *et al*., 2020). Several training systems are commonly used in viticulture, each with advantages and disadvantages. The vertical Shoot Positioning (VSP) system (Gutiérrez-Gamboa *et al*., 2021) is one of the most popular training systems, while the Y-shaped open canopy system called SAYM (Musacchi *et al*., 2021) is the new training system.

Viticultural practices can influence both the yield and wine quality of the grape. Shoot positioning can influence the metabolic change of grapevine as different training systems can affect the amount of light and nutrients the leaf and fruit receive. This can cause a change in the metabolic pathways that control the growth of the plant. Additionally, training systems can also lead to increased sugar content in the fruit, as the practice of pruning and training systems helps to balance the sink and source, and ultimately it can impact the productivity and grape quality (Cataldo *et al*., 2021b; He *et al*., 2020; Puelles *et al*., 2022; Smart *et al*., 1990; Verdenal *et al*., 2019). Manipulating leaf area exposure to maximise light interception can increase yield and grape quality (Reynolds and Vanden Heuvel, 2009). Traditional grapevine training (trellising) systems were designed to provide shading to grapes in old traditional wine regions, specifically in southern Europe and the Middle East. At the same time, those used in central Europe tended to enable higher fruit exposure to sunlight (Gambetta *et al*., 2021). VSP is a popular system that provides increased exposure to irradiation but can lead to sunburn damage (Vilanova *et al*., 2017). Consequently, alternative trellising systems such as single high-wire cordon (sprawl), head-training, tendon, pergola, Geneva Double Curtain, and closing Y-shaped open canopy **(**SAYM **)** trellis system have been proposed as suitable alternatives due to their ability to maintain bunches under a diffuse light regime and reduce direct radiation (Yu *et al*., 2022). Minimum pruning, used in the warmer viticultural area, also provides adequate shade to protect berries from sunburn (Gambetta *et al*., 2021).

This research focused on the SAYM and the VSP trellis system, two popular training systems used in arid environments. The SAYM trellis is a free-standing system with two main wires running horizontally in opposite directions and a third wire running between them at a 45-degree angle. This trellis system provides good exposure to sunlight, adequate airflow, and protection from strong winds and sun irradiance (Palliotti, 2012). In most cases, the SAYM training system is better for increased grape yield and quality since it provides shade and light exposure to the cluster zone (Musacchi *et al*., 2021). The VSP trellis system is a more radiation-intensive system that involves training the vine vertically on an overhead trellis. This system is designed to provide increased exposure to sunlight and reduce the need for manual labour (Yu *et al*., 2022). When comparing the SAYM and VSP training systems in arid environments, the SAYM trellis system is generally seen as more effective for providing shelter from sunburn due to its ability to diffuse light, provide the grape clusters with more shade for a more extended period during the day than the VSP as it has a slightly open canopy nature. In addition, the SAYM presents itself as a practical training system capable of enhancing grape and wine quality. Its simplicity and cost-effectiveness make it an easily manageable choice (Palliotti, 2012). However, the VSP system is more suitable for mechanised harvesting and offers more support to the vine. It offers effective shading for fruit, reducing potential damage from high irradiance due to its upright shoot position. In general, both the SAYM and VSP trellis systems can be beneficial in arid environments, and the choice between the two systems will depend on the specific needs of the vineyard and the nature of the grapevine variety (Arias *et al*., 2022; Ferretti, 2021; Vilanova *et al*., 2017; Yu *et al*., 2022). We hypothesised that the innovative training system known as 'SAYM' characterised by an open canopy, can significantly enhance grape and wine quality while maintaining adequate yields compared to traditional vertically shoot-positioned (VSP) trellis systems. This research aimed to compare the effects of two different training methods, SAYM and VSP, on the fruit and wine quality of the aromatic Gewürztraminer cultivar in the arid environment.

Here, we report results from a two-year project integrating wine and grape metabolic analysis and quality assessments with microclimatic and physiological measurements of desert-grown Gewürztraminer vines trained on two distinct trellising systems, VSP and SAYM.

MATERIALS AND METHODS

1. Vineyard conditions

The experimental site was located in the commercial Ramon Vineyard in the Negev Desert Highlands, near Mitzpe Ramon, Israel (30°64'31.83''N /34°77'88.64''E, 760 m above sea level). The site is an arid region, with an average annual precipitation of 69 mm (1980–2010, Israel Meteorological Service (IMS)), featuring stable meteorological conditions of high solar irradiance (10–32 MJ m^{-2} day^{-1}) and seasonal temperatures ranged from 15–38 °C (Gashu *et al*., 2020; Reshef *et al*., 2018) during the growing season. The study was based on six-year-old *V. vinifera* cv. Gewürztraminer vines cultivated for aromatic white wine production. The row orientation was 340° NNW-SSE, with a spacing of 3.0 × 1.5 m (inter- and intra-row). The experimental plot was surrounded by vineyards, except for the desert-bordering southern boundary. The vines were irrigated with surface drip irrigation, covered by a white plastic foil. A higher transpiration potential was assumed for the SAYM training system. Therefore, it was supplemented with a 60 % increase in irrigation to 1.6 L/h, whereas the irrigation rate in the VSP training system was 1 L/h. The VSP training system was implemented using an upright position of the shoots between the wires. The SAYM training system was adjusted to a Y-shaped at 90 ° opening angle (Figure 1). The training systems were distributed in a random block design with four field repetitions (rows) for each system, each containing 12–15 vines. Four vines from the middle were chosen for repetitive measurements and sampling to keep uniformity.

2. Leaf area and stem water potential measurements

In the 2017/18 season, the leaf area index (LAI) was measured fortnightly with the VitiCanopy App (Adelaide Research & Innovation Pty Ltd.), an app for measuring grapevine canopy architecture (De Bei *et al*., 2016). Photos of five plants from each treatment per repetition were taken 80 cm below the cordon. The time of the measurements was between 10:30 and 11:15, taking into consideration the zenith differences from date to date. Vine water status was assessed fortnightly through stem water potential (SWP). Five representative vines from each replication of the two training systems were marked, and a west-facing leaf was covered with a plastic bag encased in an aluminium bag. Two hours later, at noon, the leaf petioles were cut with a scalpel, and the leaf was immediately placed in a Scholander pressure chamber (PMS Instrument Company, Model 600, USA). Ψ_{stem} was recorded as soon as leaf sap was observed emerging from the cut end of the petiole (Levin, 2019).

3. Measurements of microclimatic conditions

Cluster zone radiation was measured by a spherical quantum sensor (LI-193, LI-COR, Inc. Nebraska, USA) installed in a west-facing cluster zone. The data was logged in 15-minute averages (CR10X; Campbell Scientific, USA). The VSP cluster zone radiation was measured from 5–11/6/2018, and the SAYM cluster zone radiation was measured the following week, from 13–19/6/2018. A nearby meteorological station measured incoming solar radiation (Meteo-Tech Ltd.). Since the cluster zone radiation measurements did not coincide with the two treatments, this radiation was divided by the global radiation, and the cluster zone radiation/global radiation ratio was used to compare them and determine the differences. The cluster zone temperature and relative humidity were measured by HOBO sensors equipped with an internal data logger (HOBO U23 ProV2, Onset, Bourne, MA, USA), installed in the west-facing cluster zones of three vines in each canopy treatment. Three sensors were installed in different vines for each treatment, and the sensors were monitored for two weeks. Temperature and relative humidity measurements were made at 1-minute intervals from June 5 to June 20, 2018. The data were downloaded by HOBOware software (Onset, Bourne, MA, USA).

4. Berry quality indices and yield parameters

During fruit maturation, 100 berries were collected from four marked vines (five berries from five west-facing clusters in each vine) in each replication of the two training systems. The berries were kept chilled, and quality measurements, including total soluble solids (TSS), pH, fresh weight (FW), and titratable acidity (TA), were conducted on the same day, as described by Reshef *et al*., 2018. Berries for metabolic profiling were collected into 50 ml falcon tubes, immediately frozen in liquid nitrogen, and kept in a –80 °C refrigerator until further analysis. To acquire yield parameters, each field repetition sample was harvested separately upon arrival at technical maturity (24 ° Brix; Aug 24, 2017, and July 25, 2018). Clusters were counted from at least five vines from each field repetition, and the total yield was measured with a hanging scale (HS-15K, Universal Weight Enterprise Co. Ltd., Taiwan).

5. Spectrophotometric assays for ROS detection in berries

The hydrogen peroxide concentration was determined using the methods of Yesbergenova *et al*., 2005, with the modification of a phosphate buffer pH of 6.5. It was assayed spectrophotometrically at 510 nm after 30 minutes. Superoxide anion content measurements were modified using a method (Sagi and Fluhr, 2001) based on epinephrine oxidation. Six to eight frozen (stored at –80 °C) berries were taken for each sample to adjust the protocols for berries. They were cracked, and the seeds were removed with forceps. The remaining skin and pericarp fractures were inserted into a frozen Retsch mill (Retsch MW400 model, Haan, Germany) to be pulverised for 1.5 minutes and at a frequency of 25 shakes/second. The obtained powder was transferred into new frozen 2-ml Eppendorf tubes. All processes were completed under frozen conditions using liquid nitrogen. Before testing, the frozen samples were thawed and centrifuged twice for 10 minutes at 4 °C, 14,000 rpm (Eppendorf, Germany). Each sample's fresh weight/dry weight (FW/DW) was taken by lyophilising three aliquots.

6. Photosynthetic pigment content in berry skin

We used 99 % ethanol sourced from Sigma (Sigma Aldrich-Merck KGaA, Israel) for pigment analysis, while all chemicals and solvents used were of high-performance liquid chromatography (HPLC) grade. Additionally, the HPLC-grade deionised water was generated using a Milli-Q 50 system. Peels of 50 frozen berries from each field repetition were taken, then dried by lyophilisation for 1.5 weeks, and pulverised using a Retsch-mill. Carotenoids and chlorophylls were extracted using this method (Lichtenthaler and Wellburn, 1983). In brief, 20–50 mg powder samples were immersed in 1 ml of 99 % ethanol and stored in darkness at 4 °C for 48 hours. Subsequently, the samples were centrifuged twice at 14,000 rpm for 15 minutes each, collecting the supernatant in a new tube. First, 200 µl of the extraction was loaded onto a microplate reader and read at 649, 665, and 470 nm (Tecan infinite® M200, Tecan Austria GmbH, Salzburg, Austria). The obtained optical density values were used to calculate total carotenoid, chlorophyll a, and chlorophyll b contents using the Wintermans and de Mots equation (1965). The formula used to calculate values is ca = 13.70*A665-5.76, cb = 25.80*A649-7.6*A665 ca + b = (6.10 A665 + 20.04 A649); where ca is chlorophyll a and cb is chlorophyll b. Total carotenoids calculated using the formula (1000(A470) –2.27 (A665) –81.4 (A649))/ 227. Finally, the concentrations of total chlorophyll and total carotenoids were expressed as µg total chlorophyll per gram of fresh weight (µg chlorophyll g^{-1} FW).

The entire process, from berry peeling to spectrophotometric assay, was performed under subdued (dim dark) light to avoid carotenoid degradation.

7. Winemaking

In the 2016/17 and 2017/18 seasons, wines were made separately from each field, a repetition of the two training systems. From each treatment repetition, 50 kg of harvested grape was crushed, and the must was transferred into a 25-L glass demijohn. The vinification process followed the method for white wine fermentation by Drori *et al*. (2017); with minor changes, shortly after the grapes were pressed to juice by a hydraulic press, SO_2 was added to a total of 40 ppm pectolytic enzyme (LAFAZYM® CLARIFICATION KP, Lallemand, France) added and left for sedimentation overnight at 8 °C . Following racking, the commercial yeast strain QA23 was added at 0.2 g/L, DAP was added to 150 ppm, and fermentation was conducted at 15 °C until dryness. Malolactic fermentation was prevented by the addition of 30 ppm of free SO_2 post-alcoholic fermentation. Following clarification of the wine by 0.5 g/l bentonite and sterile (0.2 um) filtration, the wines were bottled after correcting the sulfur levels to 30 ppm of free SO_2.

8. Wine tasting

A panel comprising eight highly skilled winemakers, all men between 30 and 60 years old, was assembled on March 5, 2018, at the Teperberg Winery, Zor'aa, Israel, to taste the 2017/18 wines. The parameters tested were based on the formal International Organisation of Vine and Wine (OIV) tasting form for still wines (resolution OIV/concours 332A/2009) (OIV, 2021), also used by our group previously (Netzer *et al*., 2022) with minor changes to scoring divisions between the attributes tested and terminology, as well as specifics about the tasting structure. Wines were served at 10 °C. For validation, a prior tasting was anonymously conducted by two tasters, and the scores they gave were compared to those of the broad tasting. To start the tasting, two calibration blind tastings of other wines of the same variety were conducted, and all participants publicly discussed the results to verify the proper use of terms and scales. The blind tasting of the wine samples commenced, with participants sitting around a large table, each tasting silently. The wines were tasted in pairs, and each pair randomly consisted of one SYM and one VSP sample of each of the four field replicates. A short break followed the first sitting of the two calibrations and four samples, and the last four samples were tasted afterwards. The bottles were totally covered by black cloth and coded with numbers. Using the OIV tasting method, the tasters gave grades for wine clarity (5), colour (5), aroma concentration (10), aroma typicality (varietal aroma) (6), aroma quality (19), flavour concentration (8), flavour typicality (varietal flavour) (6), flavour quality (22), harmonious persistence (aftertaste) (8), general assessment (11), and the total wine score, which is the sum of the above (a total of 100 points). The numbers in brackets represent the maximum score for each attribute.

9. GC-MS VOC analysis

The method was used by Furdíková *et al*. (2017) with some modifications. Two standard mixtures were prepared for norisoprenoids and monoterpenes. For norisoprenoids: α-ionone, pseudo-ionone, β- damascone, β- damascenone, dihydro β-ionone, theaspirane, geranyl acetone, MHO, and β-Ionone. For monoterpenes: linalool, α-terpineol, γ-terpinene, geraniol, citronellol, citral (E+Z), trans-linalool oxide, nerol, citronellyl acetate, rose oxide (E+Z), β- pinene, α-pinene, and R-limonene. Phenyl ethyl acetate, an ester, was also added. A standard stock solution was prepared by mixing 5 µl from each standard with 5 ml of methanol (the final concentration for each material was 1000 parts per million). 0.5 µl of the standard stock solution was placed in a 6-ml saturated NaCl solution for the standard mixture. Benzophenone (Sigma Aldrich-Merck KGaA, Darmstadt, Germany) was used as an internal standard. It was dissolved in ethanol to 1.6 mg/L. However, preliminary tests revealed an incomplete dissolution of the standards. Therefore, it was not used in the data normalisation. For future reference, warming the internal standard solution is advised to ensure homogeneity. Two technical repetitions were taken from each wine bottle. Then, 1 g of NaCl was inserted into 10 ml GC-MS tubes along with 6 ml of freshly opened wine and 20 µl of the internal standard solution (benzophenone, 32.8 parts per million). The tubes were immediately capped, stirred, and left for 1.5 h in Retention Time (RT) until the run.

9.1. GC-MS conditions

Volatile organic compounds (VOCs) were isolated from the headspace using solid phase microextraction (SPME; MPS2: Multipurpose sampler 2, Gertsel GmbH & Co.KG, Mülheim an der Ruhr, Germany) by divinylbenzene/carboxen polydimethylsiloxane (DVB/CAR/PDMS) 50/30 µM fibre (Supleco, Bellefonte, Pennsylvania, USA). The SPME fibre was exposed to the headspace for 30 min at 60 °C. VOCs were desorbed from the SPME fibre in the GC inlet heated to 250 °C in a splitless mode for 5 min.

9.2. Metabolic profiling

For volatile metabolite data acquisition and annotation, the Mass Hunter workstation (Agilent Technologies, version B.07.00, USA) was used based on fragmentation patterns searched against a standard library (NIST/WLAN), as well as spectral characteristics searched through the PubChem database (https://pubchem.ncbi.nlm.nih.gov). Annotation of metabolites was primarily based on RT and the m/z values of standards provided by the Lewinsohn lab. The relative contents of the detected metabolites were normalised by the median of the chromatograms' peak areas to enable comparison between different runs (Chen *et al*., 2014; Ejigu *et al*., 2013).

10. Statistical analysis

Data are presented as mean ± standard deviation (SD). On the graphs, the error bars represent standard errors (SEs). Statistical analyses were conducted using JMP 13.2.0 (SAS Institute Inc. Cary, NC, USA). A series of independent-sample two-tailed t-tests were conducted to compare the means of the quality indices, the relative metabolic contents, microclimatic data, LAI, SWP, and wine-tasting scores. R version 4.2.2 (R Core Team, 2022) was used to conduct an analysis of variance (ANOVA). A three-way ANOVA was conducted to analyse the effects of the training systems on

ROS (H_2O_2) concentrations and photosynthetic pigment content in the berries across seasons. This was followed by Tukey's HSD test for multiple comparisons. Two-way ANOVA was used to compare the means of the superoxide anion between training systems across stages.

RESULTS

1. Vine physiology

In 2016/17 and 2017/18, the SAYM's LAI was significantly higher throughout the measurement season ($p < 0.01$, Figure 2). In 2017/18, measurements started at day of year (DOY)135, when the SAYM's LAI was 58 % higher than the VSP's LAI. A necessary training adjustment was done on DOY 160 (marked by a green arrow). From this day onward, the SAYM's LAI was higher by 88.5 %, 96 %, and 118 % at DOY 164, 178, and 206, respectively, while the VSP's LAI remained constant throughout the measurement season. From DOY 164 to harvest, the SAYM's LAI increased by 20 %, and from veraison (DOY 179) to harvest, it increased by 11 %. The SAYM canopy generally boasted a notably higher LAI than the VSP, nearly doubling by the season's end. This larger canopy necessitated 60 % more irrigation to sustain stem water potential than the VSP (Figure 2).

Similarly, SWP was recorded in both training systems in the 2016/17 season, and no significant differences were found, ranging from –0.91 ± 0.11 MPa in both the SAYM and VSP (DOY 164) to lower values of –1.36 ± 0.11 MPa in the SAYM and –1.35 ± 0.1 MPa in the VSP (DOY 218). In contrast, in the 2017/18 season, the SWP pattern was characterised by shifting trends and statistically significant differences between treatments, pre and post-veraison. At DOY 178, the measured SWP in the SAYM was –1.54 ± 0.06 MPa and –1.41 ± 0.06 MPa in the VSP. Hence, supplementary tap drip lines (0.66 L/h) were used in the SAYM treatments (as well as in parallel SAYM rows) to align the SWP values of the two treatments. Two weeks later, at DOY 192, the mean of SAYM value increased to –1.34 ± 0.08 MPa, while the VSP mean plummeted further to –1.52 ± 0.08 MPa. The SWP means of the two training systems were successfully equalised only at the harvest point (–1.44 ± 0.05 MPa SAYM; –1.42 ± 0.07 MPa VSP).

2. Microclimatic conditions in the cluster zone

The diurnal pattern of incoming radiation in the cluster zone included three peaks; between 9:00 and 11:00, it reached 90.1 W/m² in the SAYM and 95.4 W/m² in the VSP; between 14:15 and 16:00, it reached 111.3 W/m² in the SAYM and 115.4 W/m² in the VSP; and between 18:00 and 18:45, it reached 44.4 W/m² in the SAYM and 55.7 W/m² in the VSP (Figure 3a). The ratio between cluster zone radiation and global incoming radiation indicates that the western side of the canopy, which is shaded until the afternoon, was not affected by treatment. In the afternoon, a clear difference between the treatments started to develop, with higher radiation intensity penetrating the cluster zone in the VSP trellising system, with the most significant difference occurring at 19:30, the time of maximum radiation penetration (Figure 3c). The diurnal temperature in the cluster zone was lower in the SAYM treatment during the daytime, reaching statistically significant differences from 9:15–11:00 ($p \leq 0.05$). The accumulated degree hour (> 30 °C degrees/hour) of 15 consecutive days in the 2017/18 growth season was 184.4 °C in the SAYM cluster zone and 5.5 % higher in the VSP cluster zone (194.8 °C), ($p > 0.05$). The diurnal SAYM cluster zone temperature values ranged between a minimum of 14.9 ± 2.8 °C at dawn (~5:45) and a maximum of 32.5 ± 3.0 °C in the afternoon (15:45). In contrast, the cluster zone temperature in the VSP was ca. 1 °C greater, having almost the same maximum temperature of 32.6 ± 2.9 °C but a lower minimum temperature (13.9 ± 3.0 °C). While the minimum temperature occurred in both treatments simultaneously (at dawn), the maximum temperature for the VSP was reached at 13:10, almost three hours earlier.

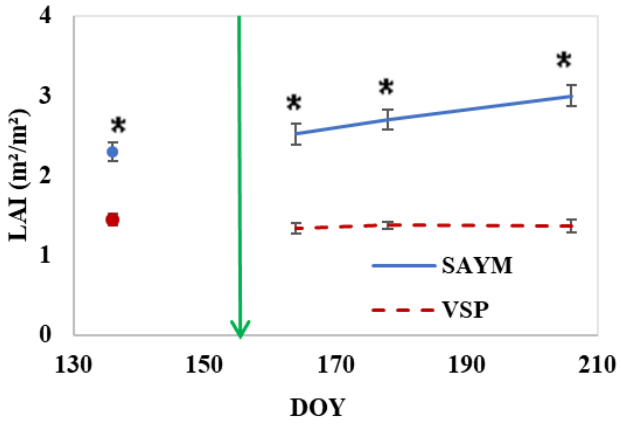


FIGURE 2. Leaf Area Index (LAI) during the 2017/18 season by the VitiCanopy app. The green arrow marks a training adjustment event. Error bars are standard errors. An asterisk indicates significant differences between training systems ($p < 0.01$). n(DOY 135) = 40, n(DOY 164) = 30, n(DOY 178) = 30, n(DOY 206) = 31.

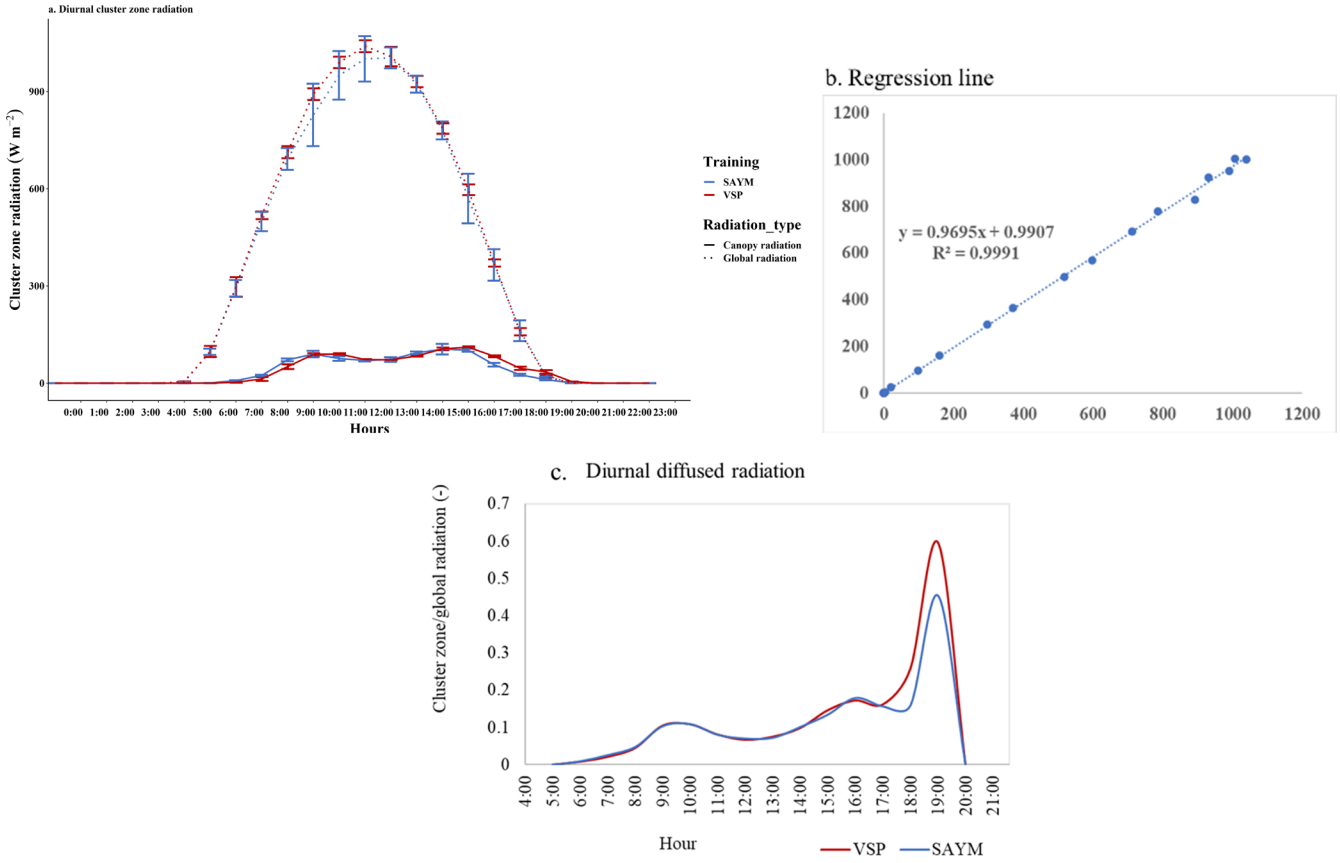


FIGURE 3. Diurnal radiation. (a) Cluster zone radiation in the SAYM and VSP treatments. Measurements were taken during two weeks (VSP: 5–11/6/2018, SAYM: 13–19/6/2018). (b) The regression line indicates the two training's radiation level was similar to the measurement done in 2017. (c) Diffused radiation in the SAYM and VSP treatments is the ratio between the cluster zone radiation and the global radiation measured during the separate weeks. Measurements were taken from the west side of the canopy.

The result we reported from the 2018 season was similar to the measurement we did in the 2016 and 2017 seasons (Figure 3b). The SAYM canopy, characterised by its more open structure, effectively reduced and postponed direct radiation exposure on grape clusters compared to the VSP system. This delay caused the maximum radiation to reach clusters around 16:00 instead of 13:00, as observed in the VSP, which is attributable to the SAYM's ability to block direct afternoon sunlight (Supplementary Figure 2). Although ambient air temperatures generally aligned between both training systems, minor differences emerged at specific times of the day. Notably, both treatments experienced cluster surface temperatures surpassing 40 °C (Supplementary Figure 4). The SAYM's canopy contributed to increased relative humidity around clusters during the afternoon compared to the VSP. This rise in humidity was likely a result of escalated transpiration from the expanded leaf area (Supplementary Figure 5). The more open structure of the SAYM canopy offered advantages in terms of delayed direct radiation and augmented humidity around clusters. However, the significantly amplified water demands may restrict its adoption in arid regions like the Negev Desert. The canopy design enhancement could potentially optimise radiation interception while mitigating irrigation needs.

3. Quality assessments

3.1. Berry quality indices and yield

In the 2016/17 and 2017/18 seasons, the SAYM berries had lower pH and higher TA values than the VSP berries (Table 1). This is evident from the lower pH values in the SAYM treatment (3.96 in 2016/17 and 3.89 in 2017/18) compared to the VSP treatment (4.2 in 2016/17 and 3.93 in 2017/18) and higher titratable acidity (TA) in the SAYM treatment (4.64 in 2016/17 and 4.70 in 2017/18) compared to the VSP treatment (3.59 in 2016/17 and 4.03 in 2017/18).

In addition, the SAYM treatment showed better quantity parameters than the VSP treatment. The SAYM treatment had higher berry FW, ranging from 0.98 ± 0.05 g in 2016/17 to 1.22 ± 0.05 g in 2017/18, while the VSP treatment had lower values ranging from 0.81 ± 0.11 g in 2016/17 to 1.08 ± 0.10 g in 2017/18. The SAYM treatment also had higher cluster weight, ranging from an average of 123.4 ± 25.3 g in 2016/17 to 147.3 ± 21.8 in 2017/18, compared to the VSP treatment values ranging from 108.7 ± 28.5 in 2016/17 to 142.1 ± 21.1 in 2017/18.

TABLE 1. Berry quality and quantity indices.

Quality/quantity index	2016/17		2017/18	
	VSP	SAYM	VSP	SAYM
°BRIX	22.8 ± 0.8	23.4 ± 0.4	24.0 ± 0.8	23.5 ± 1.5
pH	4.20+0.04*	3.96 ± 0.02	3.93 ± 0.07	3.89 ± 0.12
TA (g/L)	3.59 ± 0.08	4.64 ± 0.16*	4.03 ± 0.38	4.70 ± 0.78
Berry FW (g)	0.81 ± 0.11	0.98 ± 0.05*	1.08 ± 0.10	1.22 ± 0.05*
Yield (kg/vine)	4.5 ± 0.9	6.0 ± 1.9*	7.3 ± 1.5	8.8 ± 1.9*
Cluster weight (g)	108.7 ± 28.5	123.4 ± 25.3*	142.1 ± 21.1	147.3 ± 21.8
Clusters/vine	42.5 ± 10.8	48.9 ± 12.3	52.0 ± 10.9	60.9 ± 14.7*

*Averages ± SDs of SAYM and VSP berry quality indices and yield parameters at harvest, 2016/17–2017/18. Significantly higher values ($p \leq 0.05$) between training systems measured in the same year are denoted by an asterisk.

In the 2017/18 season, the SAYM treatment showed significantly higher cluster numbers per vine (60.9 ± 14.7) compared to VSP (52.0 ± 10.9). Additionally, SAYM demonstrated significantly higher yield per vine, with 6.0 ± 1.9 kg in 2016/17 and 8.8 ± 1.9 kg in 2017/18, as compared to VSP, which yielded 4.5 ± 0.9 kg in 2016/17 and 7.3 ± 1.5 kg in 2017/18 (Table 1). Overall, SAYM-trained berries had higher quality than VSP berries in the 2016/17 and 2017/18 seasons, with lower pH and higher TA values. SAYM berries also had higher fresh and cluster weights, more clusters per vine, and higher yield per vine. These findings suggest a positive trend in SAYM berry quality over the two seasons studied (Table 1). Generally, the grape quality from the SAYM vines exhibited higher berry fresh mass, titratable acidity, and lower pH at harvest compared to the VSP. However, no substantial differences were observed in yield, soluble solids, or quantified sunburn between the treatments.

3.2. Sensory analysis results

The SAYM wines received higher scores than the VSP wines in all categories, and a statistically significant higher score for colour, varietal characteristics (typicality) of aroma and taste, and a higher total wine score (86.86 ± 3.11 SAYM; 83.86 ± 2.12 VSP) (Table 2).

4. ROS and photosynthetic pigment content in berries

During the 2017 season, a notable disparity in ROS contents was observed in VSP berries during veraison, with higher concentrations of hydrogen peroxide and superoxide anion detected compared to SAYM berries, showcasing a statistically significant difference ($p < 0.5$). Interestingly, in the subsequent 2018 season, SAYM berries accumulated higher levels of ROS, particularly at veraison, but both training systems demonstrated lower and similar accumulations at harvest (Figure 4a,e). The dynamics of total carotenoid content seemed more influenced by the year rather than the specific training systems. This was evident through significantly higher accumulations detected during the 2018 season at the veraison stage, followed by a contrasting pattern of lower and similar responses observed at the harvest stage, showing a characteristic degradation typical of the harvest period (Figure 4b). Comparatively, the photosynthetic pigment

TABLE 2. Wine tasting of 2017/18 season, mean, and mean scores ± SEs.

Tested attributes	SAYM	VSP
Wine clarity (5)	4.5 ± 0.1	4.0 ± 0.1
Colour (5)	4.3 ± 0.1*	4.0 ± 0.1
Aroma concentration (10)	8.2 ± 0.3	7.7 ± 0.2
Aroma typicality (6)	5.3 ± 0.1*	4.6 ± 0.1
Aroma quality (19)	15.5 ± 0.3	15.4 ± 0.2
Flavour concentration (8)	7.0 ± 0.1	6.9 ± 0.1
Flavour typicality (6)	5.2 ± 0.1*	4.7 ± 0.1
Flavour quality (22)	19.9 ± 0.1	19.5 ± 0.2
Harmonious persistence (8)	7.0 ± 0.1	6.8 ± 0.1
General assessment (11)	9.9 ± 0.1	9.8 ± 0.1
Total wine score (100)	86.7 ± 0.7 *	83.7 ± 0.4 *

*Maximum score values are indicated for every tested attribute, and the total wine scores are based on their sums. Asterisks mark significant differences between treatments ($p \leq 0.05$).

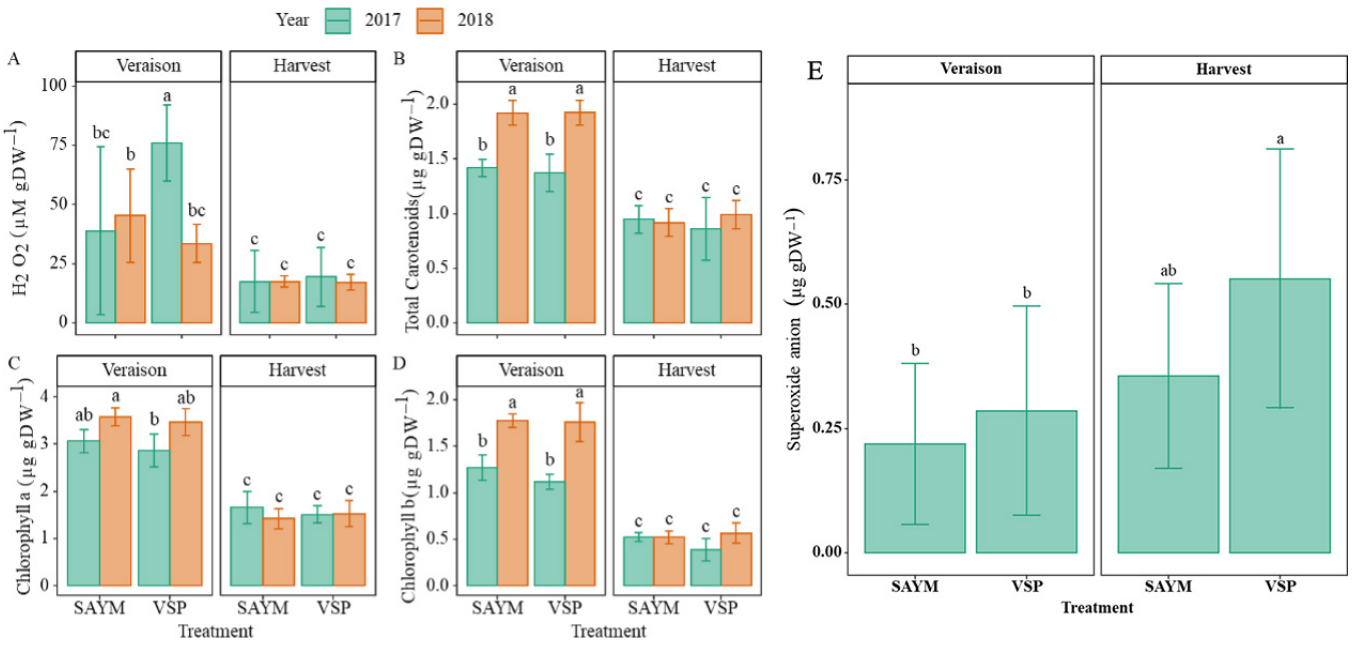


FIGURE 4. Mean ± standard deviation for ROS (Reactive Oxygen Species) levels (a), total carotenoids (b), and photosynthetic pigments (Chlorophyll a (c), Chlorophyll b (d), and Superoxide anion for the year 2017 (e)) content in SAYM and VSP berries assessed during veraison and harvest stages across the 2017 and 2018 seasons. Distinct letters denote significant variations among training systems and growth stages, determined via a three-way ANOVA with the subsequent TukeyHSD test, achieving a significance level of $p < 0.05$, n = 4–7).

content did not exhibit substantial differences between SAYM and VSP berries, except chlorophyll b, which notably increased during the 2018 season at veraison. Conversely, chlorophyll a showed a non-significant difference between the training systems (Figure 4c,d, Supplementary Table 1).

In a general sense, except for the superoxide anion, which was measured only in the 2017 season, a consistent trend emerged across ROS, total carotenoids, and chlorophyll pigments, demonstrating a characteristic decline from veraison to harvest in both treatment groups (Figure 4a–e). This temporal pattern highlights the common metabolic changes occurring from the ripening initiation (veraison) to the final harvesting stages, albeit with variations influenced by grapevine training systems and yearly fluctuations.

5. Metabolic analysis

5.1. GC-MS analysis of volatile organic compounds in wines

Esters were among the detected VOC classes, which were the most abundant in SAYM-trained vines (Table 4), with 25 identified compounds, altogether constituting over 67 % of the SAYM VOC profile and 62 % of the VSP VOC profile (Table 4). Higher ester content values were evident in the SAYM treatment (Table 4); out of the 25 identified esters, 21 were represented at higher levels in SAYM wines. However, from these differences, only isoamyl acetate was present in significantly higher content in the SAYM wines ($p \leq 0.05$) than in wines derived from VSP-grown berries (Table 4).

The second most abundant class of volatile metabolites detected in the wines were terpenoids in terms of number were the terpenoids, yet they constituted only 2.4 % and 2.7 % of the total VOCs found in the SAYM and VSP wines, respectively. While no clear link was seen between the compound relative content of this class and the training system type, three monoterpenes showed a significantly higher content ($p \leq 0.05$) in the VSP-grown berries; (E)-β-Ocimene (1.0 ± 0.18, VSP; 0.75 ± 0.08 SAYM), (Z)-β-Ocimene (0.71 ± 0.14 VSP; 0.38 ± 0.04, SAYM) and the putatively identified β-pinene (1.73 ± 0.34, VSP; 0.98 ± 0.14, SAYM) (Table 4). (E) β-Damascenone, an essential contributor to Gewürztraminer varietal aroma, was found in higher contents in the SAYM wines.

Similarly, five higher alcohols were identified; among them, the putative 2,3-butanediol was found at significantly higher levels in the SAYM wines ($p \leq 0.05$) (Table 4). This class constitutes 10.2 % of the total VOC profile of the SAYM and 11.9 % of the VSP wines' VOC profiles (Table 4). Other compounds' groups comprise classes with two representatives with a very small percentage of the VOC profile and unclassified compounds. While four out of the five compounds in the class of heterocyclic aromatic compounds (e.g., furans, pyrans, pyridine, pyrrole) had higher contents in the SAYM, the total percentage in both SAYM and VSP wines was small. The remainder of the classes (primary amine and alkaloid, ketone, thiols, and volatile phenols) did not seem to follow a specific trend linked to the training systems. Furthermore, our study demonstrated that certain varietal VOCs, including

TABLE 4. Identified VOCs and their relative content. Classes Esters, terpenoids, and higher alcohols detected in the wines are indicated under the group column. The relative content is based on the mean peak area normalised to the chromatogram median.

Compound	Relative content		Group	Odour description
	SAYM	VSP		
Succinic acid, ethyl 3-methylbut-2-yl ester	0.83 ± 0.06	0.75 ± 0.06	Ester	NA
Isoamyl Octanoate	2.61	1.74	Ester	Sweet, fruity, fatty pineapple, coconut
Pent-4-enyl formate	0.17 ± 0.01	0.21 ± 0.03	Ester	NA
Diethyl 2-hydroxybutandioate	0.65 ± 0.25	0.41 ± 0.13	Ester	NA
2-Phenethyl acetate	*46.87 ± 10.13*	*39.66 ± 7.06*	*Ester*	*Sweet, honey, floral, rosy*
Isoamyl acetoacetate	22.00 ± 4.97	22.52 ± 2.64	Ester	Sweet, ethereal, fruity, ripe banana
Isoamyl acetate	**48.21 ± 1.56**	**38.40 ± 3.17**	Ester	Pear, banana (pear drops)
Ethyl hexanoate	24.35 ± 0.94	20.10 ± 3.42	Ester	Sweet, fruity, pineapple, waxy, fatty, and estry green banana
Hexyl acetate	4.05 ± 0.59	3.41 ± 0.73	Ester	Green, fruity, sweet, fatty, fresh
Diethyl succinate	11.27 ± 2.22	10.21 ± 1.80	Ester	Mild, fruity, cooked apple, wine-like, earthy
Isopentyl hexanoate	0.52 ± 0.07	0.40 ± 0.06	Ester	Fruity, sweet, pineapple, cheesy
Diethyl glutarate	0.25 ± 0.02	0.23 ± 0.06	Ester	NA
Ethyl geranyl ether	2.22 ± 0.38	2.05 ± 0.59	Ester	Ethereal, fruity, green
Propyl octanoate	0.24 ± 0.11	0.21 ± 0.03	Ester	Coconut, cocoa, cognac
Ethyl nonanoate	0.69 ± 0.13	0.84 ± 0.13	Ester	Fruity, rose, waxy, rum, wine
Citronellyl acetate	0.89 ± 0.23	0.57 ± 0.25	Ester	Floral, rosy, green, fatty, citrus lemon and bois de rose-like
Ethyl decanoate	156.25 ± 19.72	119.79 ± 29.81	Ester	Sweet, waxy, fruity, apple
Ethyl dodecanoate	7.37 ± 1.78	7.12 ± 3.54	Ester	Sweet, waxy, soapy, rummy
Ethyl myristate	0.44 ± 0.09	0.37 ± 0.27	Ester	Sweet, waxy violet orris
Ethyl palmitate	2.52 ± 0.46	2.29 ± 1.20	Ester	Waxy, fruity, creamy, milky balsamic
Ethyl octanoate	219.29 ± 21.00	183.55 ± 48.81	Ester	Tropical fruit, pineapple, apple
Isobutyl acetate	0.96 ± 0.43	0.93 ± 0.04	Ester	Sweet, ethereal, apple, banana
Ethyl butanoate	3.25 ± 0.13	2.95 ± 0.29	Ester	Sweet, fruity, tutti-frutti
γ-Terpinyl acetate	2.06 ± 0.53	1.43 ± 0.29	Ester	NA
Linalyl butyrate (PUT)	0.68 ± 0.11	0.71 ± 0.16	Ester	Bergamot, fruity, banana, berry
2-methylbutyl octanoate	0.59 ± 0.08	0.42 ± 0.08	Ester	NA
β -Pinene (PUT)	**0.98 ± 0.11**	**1.73 ± 0.30**	Terpenoid	Cool, woody, piney, turpentine-like, minty, eucalyptus, nutmeg, spicy pepper
(Z)-β-Ocimene	**0.38 ± 0.04**	**0.71 ± 0.12**	Terpenoid	Sweet, floral, herbal
(E)-β-Ocimene	**0.57 ± 0.06**	**1.00 ± 0.16**	Terpenoid	Sweet, herbal
Linalool	*4.10 ± 0.36*	*3.84 ± 0.27*	*Terpenoid*	*Citrus, orange, floral, rose*
Hotrienol	0.58 ± 0.05	0.64 ± 0.07	Terpenoid	Sweet, fennel, ginger, tropical, spicy
α-terpineol	2.77 ± 0.23	2.78 ± 0.38	Terpenoid	Pine, lilac, citrus, woody
Nerol	*0.74 ± 0.29*	*0.71 ± 0.26*	*Terpenoid*	*Fresh, citrus, floral, green*
Citronellol	2.15 ± 0.18	2.80 ± 57	Terpenoid	Floral, rosy, sweet, citrus
Myrcene (PUT)	1.87 ± 1.27	0.21 ± 0.09	Terpenoid	Terpy, spicy, herbaceous, woody, rosy, celery, carrot
Geraniol	*0.28 ± 0.07*	*0.23 ± 0.05*	*Terpenoid*	*Rose, sweet floral-fruity rose waxy citrus*
(E) β-damascenone	2.32 ± 0.11	2.00 ± 0.43	Terpenoid	Woody, sweet, fruity, floral
Isoamyl alcohol	20.92 ± 7	22.83 ± 3.35	Higher alcohol	Pungent, fruity, banana
2,3-Butanediol (Put)	7.28 ± 1.50	6.45 ± 1.82	Higher alcohol	Fruity, creamy, buttery
2,3-butanediol (put)	**3.25 ± 0.82**	**1.48 ± 0.47**	Higher alcohol	NA
1-Hexanol	1.44 ± 0.41	1.30 ± 0.15	Higher alcohol	Ethereal, fruity, alcoholic
2-Phenylethanol	51.51 ± 9.00	55.79 ± 7.46	Higher alcohol	Sweet, floral, rose, honey, lilac

Bold letters and numbers represent significant differences between treatments at a 95 % confidence level (following a two-tailed t-test). *Italics* indicate the most important compounds typical for Gewürztraminer and showed a decreasing trend from SAYM to VSP training.

linalool, geraniol, nerol, linalool oxides, and phenethyl acetate, exhibited increased accumulation in SAYM wine while showing a decrease in VSP wines (Table 4).

DISCUSSION

This study demonstrates a relationship between reduced radiation and heat in the SAYM cluster zone and a higher quality of berries and wine, thus according to the hypothesis that an open canopy architecture can benefit viticulture in arid regions. In successive measurements of microclimate parameters such as radiation, temperature, and RH from 2016, we found a reasonably similar trend indicating that the Negev desert climatic conditions are less dynamic (Supplementary Figures 1–5). For example, the diurnal pattern of global radiation was pretty constant from the 6th of July to the 10th of August 2016/17 (Supplementary Figure 1) and also showed a similar trend in 2018 (Figure 3). The difference in light exposure between SAYM and VSP treatments is that in the VSP system, the cluster zone received significantly more radiation from the west than the east. During specific hours (13:00 to 17:30), the VSP received a maximum radiation flux of 773 ± 106 Wm^{-2} predominantly from the west, while the east-facing pyranometer recorded lower maxima (123 ± 6 Wm-2 and 108 ± 4 Wm^{-2}) with a slight decrease around noon. Conversely, in SAYM, even less radiation reached the east-facing sensor (maximum 97 ± 2 Wm^{-2}), and most of the incoming solar radiation from the west reached the cluster zone between 16:00 and 18:00 (708 ± 60 Wm^{-2} maximum). Overall, the VSP system exhibited higher daily radiation input than SAYM, mainly from east and west directions, showcasing notable differences in light exposure between the two treatments (Supplementary Figures 1–5 and 3).

The higher LAI and alleviated microclimatic conditions in the SAYM likely contributed to the improved yield obtained in the SAYM, as demonstrated by the higher ratio of clusters per vine and heavier clusters with a higher fresh berry weight. This supports the findings that excessive direct radiation and heat may reduce berry size (Hulands *et al*., 2014). Moreover, the higher ratio of clusters per vine indicates a higher production capacity of SAYM vines, which is determined by the total active leaf area (Winkler *et al*., 1974). The SAYM's LAI was higher than the VSP's, so it had more source tissues, allowing a better support of sink tissues such as clusters. In contrast, the SAYM's higher TA levels (2017/18) and lower pH levels (2016/17) contradict Palliotti's results from Sangiovese cv. grown on the same training systems (Palliotti, 2012), they do corroborate other studies that link high temperatures and lower TA (Laget *et al*., 2008; Spayd *et al*., 2002; Sweetman *et al*., 2014), as well as higher pH (Laget *et al*., 2008; Spayd *et al*., 2002). The higher pH in the VSP berries can indicate an oxidative reaction was higher than in SAYM, which can further deteriorate quality-related compounds. One of the most essential attributes of LAI can be used to predict the vine water status in semiarid vineyards where water is minimal for vine growth and development. Much research reported that LAI is strongly and significantly correlated with evapotranspiration and crop coefficients (K_c). Research on Superior Seedless (Netzer *et al*., 2009) and Cabernet Sauvignon table grape (Munitz *et al*., 2019) in semiarid vineyards demonstrates strong correlations between LAI and ETc/K_c, especially in the early season. Hence, in this research, our focus was drawn to LAI mainly. The LAI-ETc/K_c relationships allow LAI to estimate vine water needs and guide irrigation to control water status. A similar correlation was also reported in Apple orchards, which can be used to gauge plant water status using LAI (Jia and Wang, 2021). The K_c values of grapevines tend to fluctuate throughout the growing season due to differing agricultural practices (Williams and Ayars, 2005) such as irrigation (Allen *et al*., 2015) and grapevine trellising systems (Williams and Fidelibus, 2016). The canopy trellising systems had a substantial influence in this scenario, impacting the canopy structure and consequently affecting the dynamics of LAI (Netzer *et al*., 2009). These dynamics, in turn, impact the amount of solar radiation the canopy intercepts, all while being interconnected with the phenological stage of the crop (Williams *et al*., 2003).

Difficulties in equalising the SWP values between the training systems in the 2017/18 season may have caused the inter-seasonal differences in berry quality, as ROS and photosynthetic pigment contents could have been influenced by drought stress, as well as by solar irradiance with concomitant heat (Carvalho *et al*., 2015; Cramer, 2010). ROS and pigments are two crucial components of berry quality. When berries are exposed to stresses, such as drought, high temperatures, or nutrient deficiency, ROS production can increase, causing oxidative damage to the pigment molecules. This can cause a decrease in the levels of pigments, including anthocyanins and carotenoids, in the berries, resulting in a decrease in berry quality. Therefore, the relationship between ROS and pigments being affected by stresses can directly affect berry quality (Arias *et al*., 2022).

However, the 2016/17 season's SWP levels were successfully equalised between training systems. Hence, in addition to the higher berry quality and quantity in the SAYM, the lower ROS levels in the 2016/17 season's SAYM and 2018 season in VSP berries at veraison can also be attributed to the lower radiation and temperature measured in the cluster zone. Considering the oxidation damage exerted by ROS on various metabolic components, it is not surprising that wines made from SAYM berries that experienced lower levels of oxidative stress scored higher in all categories of the wine sensory assessment and retained the varietal fingerprint of Gewürztraminer wines better and SAYM training system can potentially mitigate the effects of oxidative stress in high-temperature environments.

One of the distinctions between the training systems' VOC profiles in this work was the higher content of esters in the SAYM wines. Esters are mainly produced by yeast metabolism during fermentation (Saerens *et al*., 2010; Sumby *et al*., 2010). Since the vinification process was identical for both the SAYM and VSP wines, we can assume that the ester precursor content was higher in SAYM berries, including

branched and aromatic amino acids (Antalick *et al*., 2014) and lipids, such as fatty acids. A study by Boss *et al*. (2015) highlighted the effect of β-alanine on the formation of medium-chain fatty acids and their ethyl esters and acetate esters. We propose that the higher ROS content in the VSP berries likely had detrimental effects on the substrate availability of esters, as there appears to be a correlation between ROS formation and oxidative modifications of amino acids (Suto *et al*., 2006), as well as lipid peroxidation (Farmer and Mueller, 2013). Maoz *et al*. (2018) showed that grapes have a latent ability to produce esters limited by substrate availability, namely amino acids.

The absence of norisoprenoids in the wines is worth noting. While many representatives of this class were detected in Gewürztraminer wines by Furdíková *et al*. (2017), only two norisoprenoids were identified in the Ramon vineyard wines. One of them, (E) β-damascenone, an important varietal component of Gewürztraminer wines, was found in higher contents in the SAYM wines ($p > 0.05$). This disparity between Furdíková's results and ours is most likely terroir and yeast strain-related and could stem from the Negev Desert's high temperatures. Indeed, the results of Marais *et al*. (1999) showed lower norisoprenoid levels in Sauvignon Blanc berries and wines in two warmer seasons than in a cooler one. The lack of significant differences in the norisoprenoid content between the training systems in this study accords with the lack of significant differences in their carotenoid precursor content in the berries. In 2016/17 and 2017/18, the carotenoid content in the two training systems underwent a typical decrease between veraison and maturity (Joubert *et al*., 2016; Mendes-Pinto, 2009; Young *et al*., 2016). The norisoprenoid content can be predicted (Crupi *et al*., 2010) based on this difference, yet, as mentioned earlier, this was not illustrated in the VOC profile of the Ramon vineyard wines. It is possible that norisoprenoids were formed, but the high temperatures in the Negev Desert promoted their volatilisation during ripening. A similar idea was previously proposed as an interpretation of the lower free volatile terpene content in sun-exposed Gewürztraminer berries than in partially exposed berries (Reynolds and Wardle, 1989). To fully assess the carotenoid-norisoprenoid metabolic pathway in the Ramon Vineyard's Gewürztraminer, a UPLC analysis of carotenoids from photosynthetically active pre-veraison berries is needed at the stage of carotenoid production.

The significantly higher content of some monoterpenes (Z-β-Ocimene, E-β-Ocimene, and the putatively identified β-pinene), along with a slightly higher fraction of total monoterpenes in the VSP wines, is consistent with other studies that showed an increased monoterpene pool in exposed Gewürztraminer berries (Reynolds and Wardle, 1989), Sauvignon Blanc berries (Young *et al*., 2016), and V.labruscana Golden Muscat (Macaulay and Morris, 1993). Moreover, our data suggest a decreasing trend of VOCs inherent to Gewürztraminer berries, including linalool, geraniol, nerol, and 2-phenethyl acetate from SAYM to VSP vines (Slaghenaufi *et al*., 2022). This implies an accumulation of these compounds in SAYM wines while experiencing degradation in VSP wines. This may indicate a protective response to the higher radiation and heat experienced by the VSP berries, along with higher oxidative stress levels. Several studies have suggested monoterpenes' thermo- or photo-protective roles in plants (Loreto *et al*., 1998; Peñuelas and Munné-Bosch, 2005) and their roles in quenching or neutralising ROS. For example, β-pinene, a monoterpene putatively identified to have significantly higher content in the VSP than in the SAYM, has previously been shown to reduce ROS accumulation in maize and to regulate the activity of scavenging enzymes (Mahajan *et al*., 2019).

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