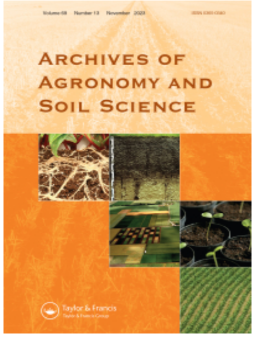

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Effects of the training system on water productivity and water footprint in Mediterranean vineyards

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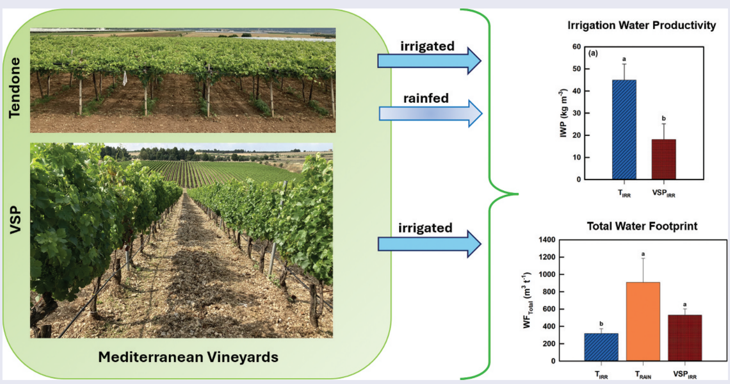
ABSTRACT

The training system is a valuable strategy to face water resource limitations under climate changes as its canopy architecture influences evapotranspiration losses and both water productivity (WP) and irrigation water productivity (IWP). Detailed information on them (yield per unit of water) would support the choice of the training system. This study compared the water productivity in 38 irrigated ($_{IRR}$) and rainfed ($_{RAIN}$) vineyards trained at tendone (T, $n = 30$) and vertical shoot positioning (VSP, $n = 8$). The green, blue and grey volumetric water footprints (WFs) were also employed to characterize T and VSP. At harvest, grape quality traits (pH, sugars and potassium concentrations) were examined too. The mean (±SE) IWP in T_{IRR} reached 45.0 ± 7.2 kg m^{-3} being approx. 2.5-fold than that in VSP_{IRR}. Furthermore, T_{IRR} showed 60% (WF_{green}) and 30% (WF_{blue}) lower than VSP_{IRR}. Findings show the attitude of T_{IRR} in valuating water resources with no significant impact on grape quality. This study integrates the set of knowledge to be evaluated for training system choice managing the trade-offs between yield, grape quality and water productivity triggered by climate change.



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Introduction

According to IPCC et al. (2022), semi-arid regions around the world are increasingly facing significant challenges related to climate change. Indeed, these regions are projected to become drier, which will lead to more frequent and severe droughts. Water scarcity and in turn drought events are expected to worsen due to decreasing annual precipitation and increasing air temperature (Lionello and Scarascia 2018). This trend is expected to have significant impacts on agriculture, which is a major user of water. According to IPCC et al. (2022), Mediterranean Europe is already experiencing water scarcity and facing significant challenges related to agriculture water management. In addition, water scarcity in Mediterranean areas, as well as other semi-arid regions worldwide, will likely lead to changes in crop species and irrigation practices, adopting more drought-tolerant ones and implementing water-saving technologies (IPCC et al. 2022). However, in case of relevant socio-economic species such as *Vitis spp*. (a global surface area equal to 7.3 million of hectares according to OIV 2023), substitution is not easily feasible (Naulleau et al. 2021)

Irrigation commonly compensates for soil water content to satisfy plant needs; therefore, it affects canopy development, yield and fruit composition. Hence, a lack of water could determine the restriction in terms of vegetative and reproductive growth (Kramer and Boyer 1995). Several strategies have been used in recent decades to adapt to environmental constraints resulting from climate change (*e.g.*, PRD, RDI, priming, leaf thermoregulation) (Flexas et al. 2010; Montanaro et al. 2022) become pivotal also to keep grape and wine quality (Chaves et al. 2007).

It is worth to notice that grapevine is a drought tolerant plant, cultivated since millennia in arid and semi-arid regions of Asia, Europe and Africa (Dong et al. 2023). Besides the selection of drought tolerant scion (Lovisolo et al. 2010) and rootstock (Bianchi et al. 2018), the vineyard management techniques could significantly affect the water productivity (WP), resulting in key adaptive responses. Among them, the training system, modifying the plant architecture, significantly impacts the vegeto-productive performances and water use of vineyards (Reynolds and Heuvel 2009; Del Zozzo et al. 2024).

In the Mediterranean and semi-arid areas, in order to avoid water waste, it is mandatory to find management strategies able to optimize the water use efficiency (WUE) (Medrano et al. 2015). For this purpose, several approaches were developed for measuring grapevine water status and WUE (reviewed in Medrano et al. 2015) that can be determined at different scales. For example, Medrano et al. (2015) identified the following: leaf scale (Net leaf photosynthesis/transpiration or stomatal conductance), watershed scale (yield/water used), plant (biomass/water loss) and vineyard scales (yield/water used, WUE_{crop}). WUE reflects a balance between ‘gains’ and ‘costs’ (Tomás et al. 2014). It is worth to notice that WUE can be analyzed at different spatial/temporal horizon (Medrano et al. 2015) and vineyard conditions (*e.g*. irrigation management, soil humidity content, meteorological conditions (Balbontín et al. 2015)). Although the WUE_{crop} is suitable to analyze the influence of management practices (Sadras 2009; Williams et al. 2010), it is difficult to be employed at commercial scale due to the uncertainties in determining the vineyard water used accounting for the amounts of water losses (*e.g.*, evaporation, run-off, leaching *etc*.) (Sadras 2009; Medrano et al. 2015). Hence, the ‘irrigation water productivity’ (IWP) (yield per unit of applied irrigation water) has been suggested to measure the irrigation efficiency at commercial scale (Sadras 2009) gathering the concept from the water productivity (WP) mostly expressed as the ratio of ‘biomass to evapotranspired water’ as reviewed in Steduto et al. (2007), which reported that WP is also referred to as WUE in the literature.

Due to the increased necessity of mechanization, some trellises well adapted in semi-arid viticulture areas, such as *Gobelet* and horizontal canopy systems like *Pergola* and *Tendone*, have been replaced by vertical shoot positioning (VSP) ones, pruned as spur cordons or Guyot (Kurtural and Fidelibus 2021). Although VSP has some limitations in facing climate change challenges being prone to radiative stress and heat wave (Gutiérrez-Gamboa et al. 2021), it is widely adopted in different environments. The *tendone* (T) training system is widely adopted in warm/dry environments offering bunch and soil shading, which are in favour of grape quality and evaporation reduction being valuable traits in Mediterranean areas (Xyrafis et al. 2023).

The T and VSP training systems differ in various agronomical traits including bud load per hectare, total leaf area, shaded/exposed leaf ratio leading to different yield and water requirement (Pastena 1990). It is also reported that they differ in terms of water consumption, while the production could be comparable depending on the vintage (Giorio and Nuzzo 2011; Silvestroni et al. 2019, 2020; Alba et al. 2022). Following this, it could be argued that the T and VSP have a different WP at vineyard scale.

To account for the environmental and socio-economic impacts of the agrifood production, the concept of 'virtual water' has been worldwide introduced quantifying the volume of water used to produce a commodity (Allan 1998). In line with this, the water footprint (WF) is defined as the volume of water used per unit of food produced safeguarding water resource (Mekonnen and Hoekstra 2011). Hoekstra (2011) proposed an operational WF scheme splitting the volumes of water used along the production chain into three fractions: green (the rainwater consumed for crop yield), blue (the irrigation water consumed for crop yield) and grey (the freshwater required to assimilate pollutants). The above green, blue and grey volumes of water normalized per unit yield translate into WF_{green}, WF_{blue}, WF_{grey} (usually m^3 water t^{-1} yield), respectively (Hoekstra 2011).

The various WFs calculated as above give volumetric data about the virtual water requested for production as well as its impact on local and global water resources (Mekonnen and Hoekstra 2011). Within the agriculture context, WFs have been applied to estimate the socio-economic environmental impact of various crops including apple, orange, peach, cotton and grapevine (Mekonnen and Hoekstra 2011). Hence, the use of WF to compare the efficiency of water use in different training systems might provide additional information on their environmental impact, aiding the selection of the best adaptive one in a challenging viticulture scenario worldwide (IPCC et al. 2022). On this background, the work aims at comparing the IWP and WFs in T and VSP vineyards. The results provide new insights about adaptative strategies in growing grapes through assessing the impact/role of training system on water as crop (IWP) and environmental (WFs) valuable resources.

Materials and methods

Viticulture experimental design

Thirty-eight vineyards (cultivar 'Montepulciano') belonging to private farms were located in coastal (min. distance from the sea: 1.5 km) and hilly areas (max distance from the sea: 20 km) of the Molise region (South-East Italy). The vineyard elevation ranged from 15 m to 546 m asl. The studied area is shown in Figure 1, while details concerning the vineyards (location; training system; pruning, irrigation and soil management; area and plant distribution; grape production) are reported in Supplementary materials (Table S1, S2 and S3; Figure S1). Briefly, 30 T (vine density from 1600 to 2800 vines ha^{-1}) and eight VSP (vine density from 2666 to 9259 vines ha^{-1}) vineyards were studied. The training systems were characterized by a cane pruning management. Twenty vineyards (18 T and 2 VSP) were rainfed, while the other 18 were irrigated in June, July and August according to the local irrigation scheduling.

According to the local commercial practices, at harvest time (from 22nd Sept. to 15th Oct.), per each vineyard the yield was obtained by weighting the total grape production (by the means of a standard platform scale, Bilanciai D 800, 1.0 kg – Barletta, Italy) upon delivery to the cellar of the cooperative winery 'Cantina San Zenone'. Must samples from different points (at least 3) for each trailer were automatically collected using a vertical screw inserted into a steel tube. Sugar concentration (°BABO) and pH of the must samples were determined using a multiparameter analyzer (Maselli sm-02, Maselli Misure S.p.A. Parma, Italy). The sugar yield (t ha^{-1}) was obtained multiplying the grape yield per the sugar concentration of grapes. Total anthocyanins (mg L^{-1}), total phenolic compounds (mg L^{-1}) and potassium

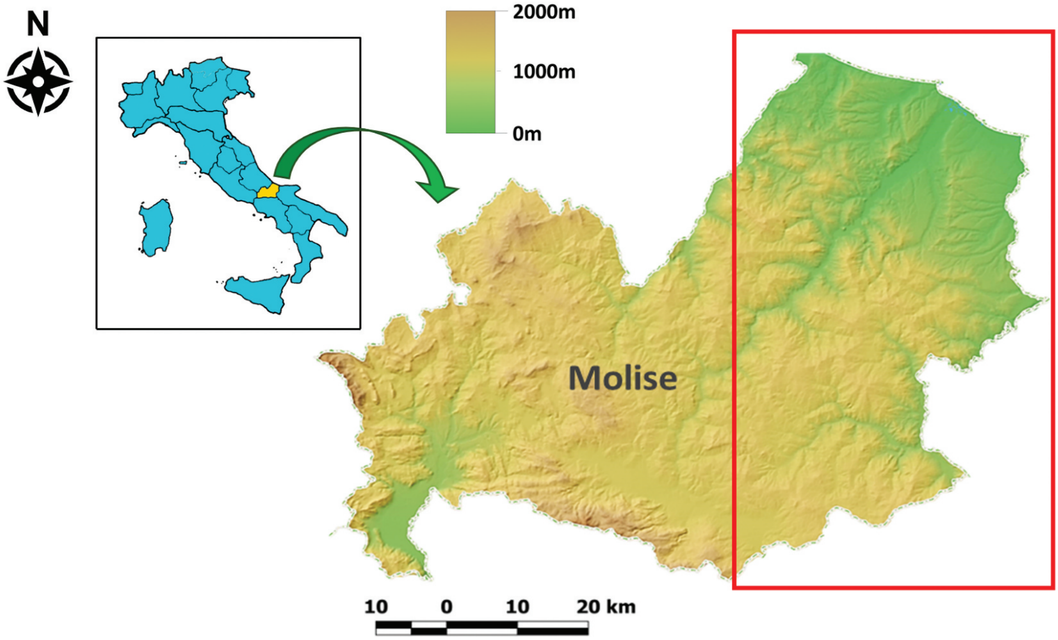

Figure 1. Overview map of the study area. Within the inset the map of Italy, highlighting in yellow the Molise region. In the digital terrain model of the region the red rectangle indicates the area pertaining the studied vineyards.

(mg L^{-1}) were determined using a sequential enzymatic analyzer, Y15 from BioSystems (Barcelona, Spain). The Y15 equipment was calibrated with the external standards that are provided in every kit by BioSystems.

Water productivity (IWP) and water footprint (WF)

The irrigation water productivity (IWP) was calculated as the ratio between yield (kg ha^{-1}) and the volume of irrigation water supplied to each vineyard (m^3 ha^{-1}), according to Sadras (2009).

The total water productivity (WP_{TOTAL}) was calculated as the ratio between yield (kg ha^{-1}) and the sum of the rainfall + irrigation volumes (m^3 ha^{-1}).

$$\mathrm{IWP} = \frac{\mathit{Yield}\ (\mathrm{kg\ ha}^{-1})}{\mathit{applied\ irrigation\ water}\ (m^3\ \mathrm{ha}^{-1})} \tag{1}$$

$$\mathrm{WP_{TOTAL}} = \frac{\mathit{Yield}\ (\mathrm{kg\ ha}^{-1})}{\mathit{applied\ irrigation\ water} + \mathit{annual\ rainfall}\ (m^3\ \mathrm{ha}^{-1})} \tag{2}$$

The volumetric WF was calculated according to Hoekstra (2011) and partitioned in the 'green', 'blue' and 'grey' component as follows:

$$\mathrm{WF_{green}} = \frac{\mathit{rainfall}(m^3\mathrm{ha}^{-1})}{\mathit{yield}(t\mathrm{ha}^{-1})} \tag{3}$$

$$\mathrm{WF_{blue}} = \frac{\mathit{irrigation\ water}\ (m^3\ \mathrm{ha}^{-1})}{\mathit{yield}\ (t\ \mathrm{ha}^{-1})} \tag{4}$$

$$WF_{grey} = \frac{(\alpha \times AR) \div (c_{max} - c_{nat})}{yield(tha^{-1})} \tag{5}$$

The rainfall volumes used in the Equations 2 and 3 refer to the total annual rainfall (m^3 ha^{-1}) of the area pertaining the vineyards according to their elevation (Figure S1).

According to Mekonnen and Hoekstra (2011), in Equation 5, the grey WF is related to nitrogen (N), AR represents the annual N application rate (kg ha^{-1}), α represents the fraction of AR assumed to be lost via leaching or run-off (10%), C_{max} is the maximum acceptable concentration of N in the water body (kg m^{-3}), C_{nat} is the natural concentration of N in the receiving water body which was assumed to be zero. Following Mekonnen and Hoekstra (2011), C_{max} was set to 10 mg L^{-1}. The AR in each vineyard was related to the fertilization plan receiving 45, 30 and 25 kg ha^{-1} when under mineral, organo-mineral and organic fertilization, respectively. Four vineyards did not receive N. The sum of the three WF components represents the total WF (WF_{total}).

Data analysis

Vineyard groups were compared by using the Student's *t*-test after checking for the normality distribution of data (Shapiro – Wilk's test); in case of failure of the test, the non-parametric Mann-Whitney's U-test was used. Values of *p* lower than 0.05 were considered significant. Data analysis, fitting curve and plotting were by Sigmaplot 12.3 (Systat Software Inc.).

Results

The meteorological data collected from the various weather stations provide the seasonal pattern of the precipitation and temperature throughout the analyzed area according to their elevation a.s.l. (Figure 2). Annual and seasonal (JJA) mean rainfall and temperature are reported in Supplementary material (Table S2).

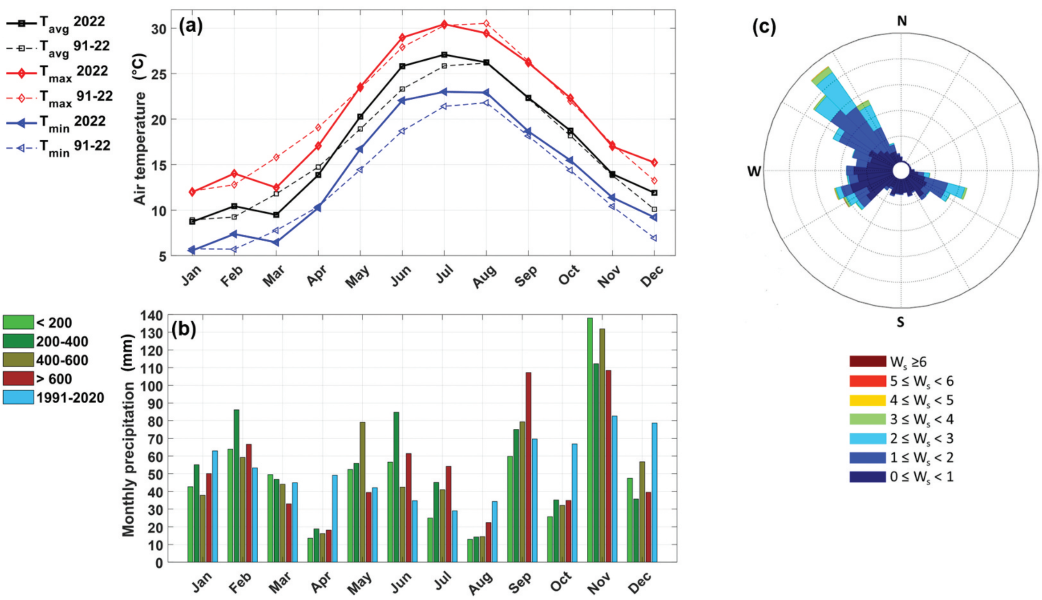

Figure 2. (a) Monthly minimum (solid blue line), mean (solid black line) and maximum (solid red line) temperatures for the year 2022. Dotted lines represent the average temperatures for the period 1991–2020. (b) Monthly cumulative precipitation at different elevation (from <200 to >600 m asl) during 2022. The light blue bar represents the average cumulative precipitation for the period 1991–2020. (c) Distribution of wind speed (W_s; m s^{-1}) and direction measured during 2022.

Yield and grape composition

The yield in T ranged from 0.9 to 47.6 t ha^{-1}, while it varied from 7.5 to 23.7 t ha^{-1} in VSP (Figure S1). The vines under irrigation received on average 665 ± 106.8 and 697 ± 226.3 m^3 of water per ha in T and VSP, respectively (Table S3).

Regardless of the training system, the concentration of the total anthocyanins was significantly low in irrigated fields being approximately 60 and 104 mg L^{-1} in irrigated and rainfed vineyards, respectively (Table 1). Similarly, total polyphenols were significantly influenced by treatment reaching approx. 780 and 1130 mg L^{-1} in irrigated and rainfed vineyards, respectively (Table 1). The sugar concentration (~20 °BABO) and the other analyzed traits were comparable in irrigated and rainfed vineyards (Table 1). When analyzed regardless of the training system, the irrigation significantly affected the yield reaching 20.36 ± 12.39 t ha^{-1}, while it was 13.03 ± 9.45 t ha^{-1} in rainfed plots (Table 1). When analyzed regardless of the water source (irrigated, rainfed), the training system did not significantly influence the analyzed traits (Table 2).

Irrigation water productivity (IWP)

The average (±SE) annual volume of irrigation water received by the vineyards was 664.7 ± 106.8 in T_{IRR} and 1002.2 ± 226.3 m^3 ha^{-1} in VSP_{IRR} and was statistically comparable (Student's *t*-test, $\alpha = 0.05$).

The average IWP in irrigated T vines (45.0 ± 7.2 kg m^{-3}) was significantly higher with respect to irrigated VSP ones (18.1 ± 7.1 kg m^{-3}), as shown in Figure 3(a). When the efficiency of water used accounted for the sum of irrigation + rainfall volumes (WP_{TOTAL}), it showed significant differences among T_{IRR} (4.4 ± 0.7 kg m^{-3}), T_{RAIN} (2.5 ± 0.5 kg m^{-3}) and VSP_{IRR} (2.2 ± 0.3 kg m^{-3}) vineyard groups Figure 3(b).

Results on the volumetric WF show that the WF_{green} reached 267.1 ± 47.3, 842.1 ± 251.0 and 404.4 ± 50.3 m^3 t^{-1} in T_{IRR}, T_{RAIN} and VSP_{IRR}, respectively (Figure 4). As concerning WF_{blue}, T_{IRR}

Table 1. Mean (± SD) yield and measured grape quality traits (sugar, pH, potassium, anthocyanins and total polyphenols) in irrigated and rainfed vineyards regardless of training system (*indicates significant differences; ns, not significant at, $p = 0.05$). Note that the comparison of yield and total anthocyanins employed Student's *t*-test, while sugars, pH, potassium and total polyphenols were compared using the Mann-Whitney U-test).

Parameters	Irrigated	Rainfed	Significance
Yield (t ha^{-1})	20.36 ± 12.39	13.03 ± 9.45	*
Sugar (°Babo)	20.17 ± 0.90	20.17 ± 1.75	ns
Sugar (t ha^{-1})	4.06 ± 2.39	2.64 ± 1.95	*
pH	3.51 ± 0.14	3.42 ± 0.15	ns
K (mg L^{-1})	1708.11 ± 146.99	1711.90 ± 197.28	ns
Anthocyanins (mg L^{-1})	59.89 ± 44.02	104.53 ± 58.07	*
Polyphenols (mg L^{-1})	780.29 ± 316.20	1129.22 ± 372.85	*

Table 2. Mean (± SD) yield and measured grape quality traits (sugar, pH, potassium, anthocyanins and total polyphenols) in Tendone and VSP vineyards regardless water management (ns, not significant at, $p = 0.05$). Note that the comparison of yield and total anthocyanins employed Student's *t*-test, while sugars, pH, potassium and total polyphenols were compared using the Mann-Whitney U-test).

Parameters	Tendone	VSP	Significance
Yield (t ha^{-1})	17.09 ± 5.84	14.26 ± 12.49	ns
Sugar (°Babo)	17.09 ± 5.84	20.49 ± 1.28	ns
Sugar (t ha^{-1})	3.41 ± 2.46	2.95 ± 1.32	ns
pH	3.45 ± 0.17	3.49 ± 0.08	ns
K (mg L^{-1})	1702.28 ± 163.39	1738.25 ± 211.26	ns
Anthocyanins (mg L^{-1})	87.52 ± 59.24	65.75 ± 39.31	ns
Polyphenols (mg L^{-1})	1022.18 ± 376.15 a	749.00 ± 356.21 a	ns

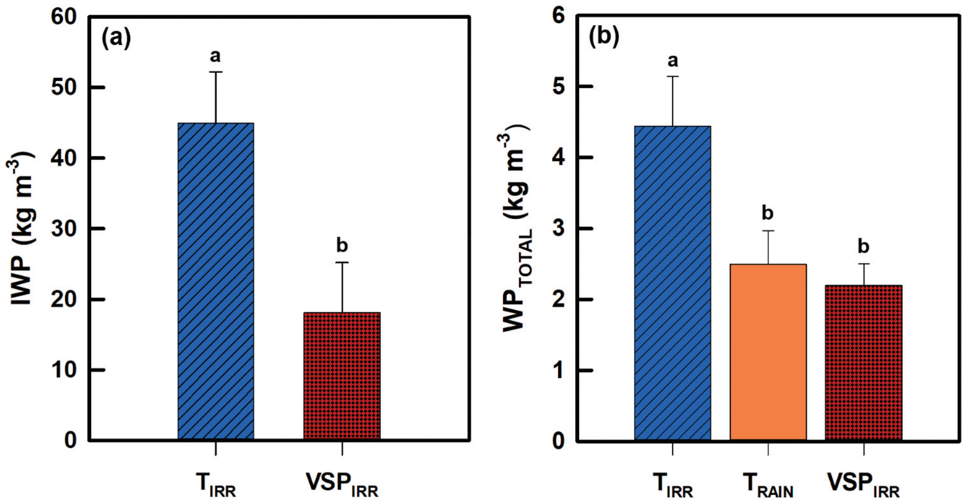

Figure 3. (a) Irrigation water productivity (IWP) calculated in both irrigated Tendone (T_{IRR}) and irrigated vertical shoot positioning (VSP_{IRR}) vineyards. (b) Total water productivity (WP_{TOTAL}) calculated in irrigated Tendone (T_{IRR}), rainfed Tendone (T_{RAIN}) and irrigated vertical shoot positioning (VSP_{IRR}) vineyards. Different letter indicates statistically significant difference ($p < 0.05$).

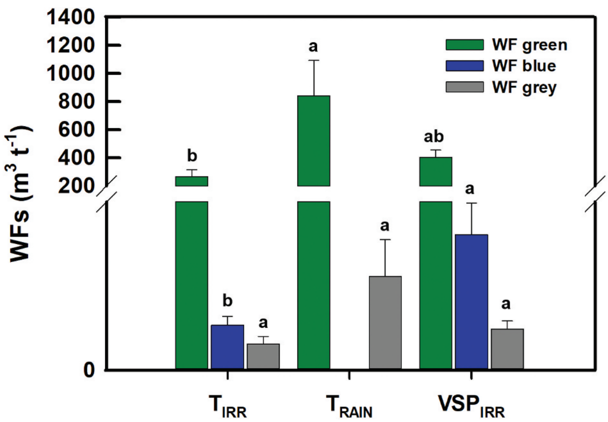

Figure 4. Green, Blue and Grey Water Footprint in irrigated (T_{IRR}) and rainfed tendone (T_{RAIN}) and irrigated vertical shoot positioning (VSP_{IRR}). Comparing the same water footprint category, different letter indicates significant differences across all groups ($p < 0.05$). The Y-axis has been broken from 120 to 200 m^3 t^{-1}.

displayed a significantly lower value of 32.4 ± 6.1 m^3 t^{-1} against that in irrigated VSP which reached 96.7 ± 22.4 m^3 t^{-1}. The WF_{total} was significantly lower in T_{IRR} (318.3 ± 55.8 m^3 t^{-1}) than T_{RAIN} (908.9 ± 276.8 m^3 t^{-1}) and VSP_{IRR} (530.5 ± 71.4 m^3 t^{-1}) (Figure 5).

Discussion

This study compared the water use in two training systems that received water through irrigation and/or precipitation, assessing (i) the irrigation water productivity (IWP) (Sadras 2009) and (ii) the volumetric water footprint (WF) (Hoekstra 2011). Findings documented that T and VSP did not have a significant impact on grape quality traits and that T_{IRR} significantly increased IWP by approx. 60% when compared to $VSP_{IRR.}$ The analysis also revealed that the socio-economic impact was minimized in T_{IRR} (*i.e.*, lowest WF). Hence, the present study contributed to characterize these systems which are

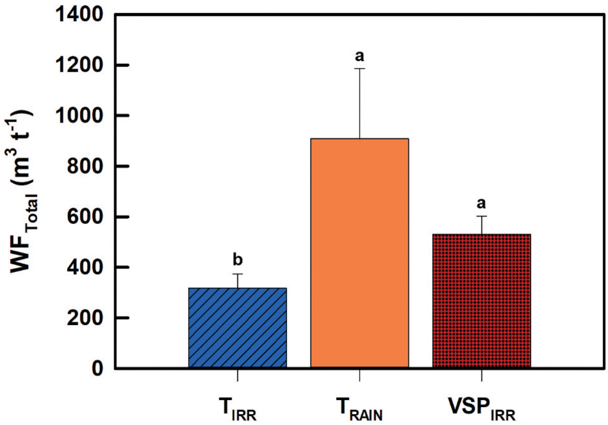

Figure 5. Total Water footprint ($WF_{green} + WF_{blue} + WF_{grey}$) in irrigated ($T_{IRR}$) and rainfed tendone ($T_{RAIN}$) and irrigated vertical shoot positioning (VSP_{IRR}). Different letter indicates significant differences between vineyard groups ($p < 0.05$).

relevant trellises for the grapevine industry in Mediterranean environment (de Palma and Novello 2003; Giorio and Nuzzo 2011; Vanino et al. 2015; Gutiérrez-Gamboa et al. 2021; Alba et al. 2022; Del Zozzo et al. 2024).

The relatively high number of vineyards analyzed in the present study and their distribution over a large and variable area *(e.g.*, elevation range) support the reliability of the outcomes. Environmental conditions might influence water consumption and yield (Gutierrez-Gamboa et al., 2021) and therefore might be influential on IWP and WF (Balbontín et al. 2015). The mean air temperature and the rainfall recorded were in line with typical Mediterranean climates, and the mean values of the area (Aucelli et al. 2007), further supporting the study's reliability. The annual pattern of precipitation aligns with the values reported by the above-mentioned study, underscoring the key role of elevation in shaping regional climate dynamics. The complete alignment between our results and the existing literature, together with the observed temporal consistency, underscores the climatic representativeness of the year investigated.

The training systems compared in this study usually differ in both reproductive and vegetative parameters, such as bud load per hectare and leaf area (Giorio and Nuzzo 2011; Silvestroni et al. 2019, 2020) as well as canopy architecture (Pastena 1990; de Palma and Novello 2003). However, these parameters do not fully support identifying the best one concerning the efficiency of water use which is a pivotal climate change adaptation strategy (Medrano et al. 2015). Therefore, our findings on IWP and WF would expand knowledge on this specific topic, possibly contributing the selection of the best training system.

The yield was significantly affected by the water received as irrigation (*i.e.* rainfall + irrigation) (Table 1 and Figure S1) which fits with the existing literature (Williams et al. 2010; Torres et al. 2021). On the contrary, in our conditions, the training system did not exert any significant influence on yield (Table 2). The volume of irrigation water received by vines was not statistically different between T and VSP (see Results section), despite it generated an overall improvement of the IWP in T_{IRR} training system. This result is difficult to discuss due to the poor literature existing on this specific point. However, IWP in T_{IRR} was approx. 2.5-fold than that in VSP_{IRR}, suggesting that the allocation of water resource to sustain grapevine yield is advisable when the T system is employed. As a result of the relatively wide range of irrigation volume supplied in T and VSP training systems, the correlative information between IWP and irrigation volumes (Figure 6) highlight that IWP in T_{IRR} is kept consistently higher than that in VSP_{IRR} even at high irrigation volume (~900 m^3).

The analysis of IWP is in favour of T system which apparently contrasts with the general classification of T as a non-recommended training system under water stress, as advised in Del

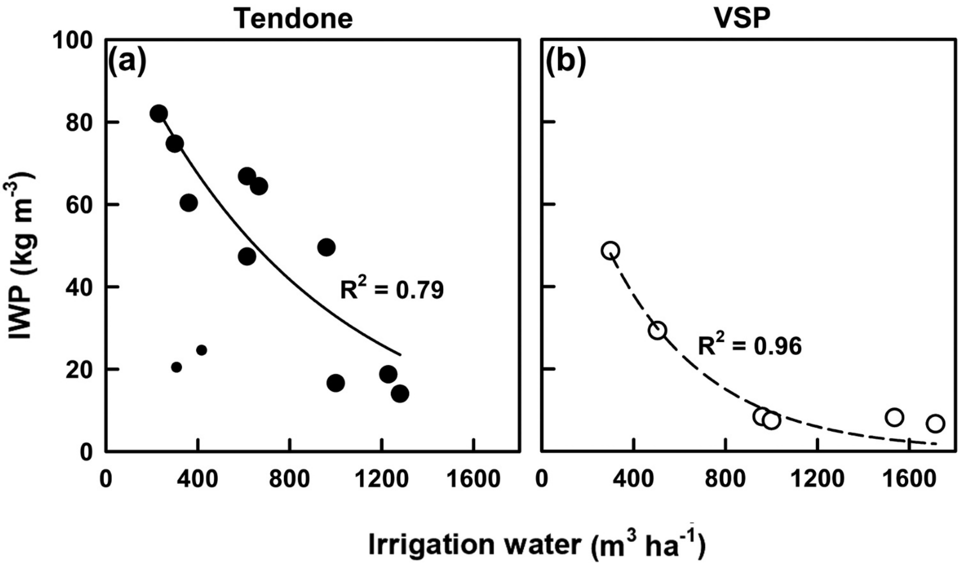

Figure 6. Correlation between irrigation water and IWP in (a) irrigated T and (b) VSP. Note that the smaller dots in panel 'a' were not considered during the fitting procedure. An exponential decay regression model ($y = a^*e^{-bx}$) was used to correlate the irrigation water productivity to the seasonal irrigation water. For both training systems *'a'* and *'b'* were statistically significant at $p < 0.001$. In the tendone, '*a*' was 108.72 and '*b*' 0.0012, in VSP '*a*' was 95.61 and '*b*' 0.0023.

Zozzo et al. (2024). The high IWP found in T_{IRR} was due to the intrinsic capacity of the tendone trellising to optimize the yield per hectare once irrigated. In addition, the spatial leaf area distribution per hectare was conceivably improved in T (de Palma and Novello 2003; Giorio and Nuzzo 2011; Silvestroni et al. 2020) compared to the VSP likely increasing leaf WUE and reducing soil evaporation. Indeed, the T system usually displays the highest soil shade index (leaf area to soil surface area ratio), comparing with other training systems such as VSP (Giorio and Nuzzo 2011 and references therein). The soil shading, reducing the soil surface temperature, is expected to significantly reduce the water lost through evaporation (Breshears et al. 1998). Furthermore, T would not determine a significant shading between the main and the lateral leaves in the upper canopy layer, while determines a steady shading along the canopy profile contributing to minimize transpiration loss (Giorio and Nuzzo 2011). Thus, the *tendone* canopy, because of the ability to cover the whole available soil surface, optimizes the photosynthetically active radiation interception, thus putatively leading to a high photosynthate production useful for vine dry matter accumulation and berry ripening (Kliewer and Dokoozlian 2005).

Concerning grape quality, it is worth noting that rainfed and irrigated vineyards were comparable in terms of sugars, pH and potassium (Table 1). On the contrary, grape from rainfed vineyard displayed significantly higher total anthocyanins and total polyphenols (Table 1) compared to that in irrigated. In this study, we did not measure any physiological trait to serve as proxy of vine water status (*e.g.*, stem water potential, stomatal conductance). However, the rainfed vineyard would have suffered water limitation, at a conceivable greater extent than irrigated. Hence, the high values of anthocyanins and total polyphenols in rainfed grape are consistent with the evidence that flavonoids strongly respond to abiotic stressors such as drought, which generally stimulate secondary metabolisms (Gambetta et al. 2020). However, this remains to be specifically tested.

Although the training system did not differentiate the quality of bunch, additional advantages embedded in the T system to face the new challenges posed by climate change should be evoked. For example, overhead canopy training systems like *pergola* and *tendone* protect the bunches from direct sunlight, thus avoiding the excessive berry heating and skin radiative stresses that can lead to grapes with poor anthocyanin contents (Spayd et al. 2002) and sunburn symptoms (Rustioni et al. 2023).

Considering that the response of yield to increasing volume of water received follows an asymptotic pattern after an initial quasi-linear correlation (Williams et al. 2010), which was expanded in the T system compared to VSP (Figure 6). As a result of this, the WP_{TOTAL} in irrigated T vineyards was at a significantly higher level Figure 3(b), confirming the influence of the training system on water use.

In the present study, the total water cost for a vineyard to get yield was expressed as WP_{TOTAL} (Equation 2), in which both irrigation volume (m^3 ha^{-1}) and annual rainfall (m^3 ha^{-1}) were considered as water sources feeding the vines. The former is managed by the grower during the vegetative season, whereas the latter is relevant in refilling the groundwater reserves (Muratoglu et al. 2023) and still important in supporting grapevine water demand (Campos et al. 2016).

Hence, increasing soil structure and function maximizing soil water infiltration (*e.g*., Montanaro et al. 2018), water rate would be in favour of high WP_{TOTAL} throughout optimizing crop yield.

A comprehensive picture of the environmental impact of vineyard yield on water resources (WFs) needs the evaluation of both green (rain) and blue (irrigation) water. According to training system, the analysis of the volumetric WF showed that the WF_{green} in the T_{RAIN} was three times higher than that in T_{IRR}, confirming the important role of irrigation in lowering the footprint via increasing yield (see above the discussion on IWP) within the same training system.

Furthermore, comparing the two training systems supplied by irrigation water, the T_{IRR} was characterized by lower WF_{blue} compared to VSP_{IRR} highlighting the capacity of the overhead training system to optimize the efficiency of the applied water resource, as it is advisable in sustainable irrigated viticulture (Torres et al. 2021).

By combining the green, blue and grey WF categories in the WF_{total}, a comprehensive assessment of the socio-economic footprint might be envisaged (Mekonnen and Hoekstra 2011 and references therein). In this study, WF_{total} ranged from approx. 150 to approx. 2000 m^3 of water t^{-1} of fresh grape across the vineyard categories, which is in line with published WF_{total} in grapevine (Mekonnen and Hoekstra 2011; Torres et al. 2021). It can be noted that WF_{total} in T_{RAIN} and VSP_{IRR} were comparable and averagely 50% higher than that in T_{IRR} confirming the allocation of irrigation water is more sustainable that in VSP.

Conclusions

The present study contributed to characterize the water productivity of T and VSP training systems and the results expand current knowledge on water use in viticulture supporting sustainable training system selection under climate change. Data clearly showed that T_{IRR} has had higher IWP compared to that of the VSP_{IRR}. The socio-economic evaluation of the water used by the training system revealed the reduction of the footprint achieved at the T system when applying irrigation via increasing productivity with no impact of grape quality traits. Hence, this study integrates the set of knowledge to be evaluated for training system choice managing the trade-offs between yield, grape quality and water productivity triggered by climate change.

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