Effect of Irrigation with Treated Municipal Wastewater on *Vitis vinifera* L. *cvs.* Cabernet Sauvignon and Sauvignon blanc in Commercial Vineyards in the Coastal Region of South Africa - Vegetative Growth, Yield and Juice Characteristics

K. Hoogendijk[1,2], P.A. Myburgh[1], C.L. Howell[1]*, E.L. Lategan[2,3] and J.E. Hoffman[2]

(1) ARC Infruitec-Nietvoorbij[1], Private Bag X5026, 7599, Stellenbosch, South Africa.
(2) Soil Science Department, Stellenbosch University, Private Bag X1, 7602 Matieland, South Africa.
(3) Formerly ARC Infruitec-Nietvoorbij, Private Bag X5026, 7599, Stellenbosch, South Africa.

Submitted for publication: June 2023
Accepted for publication: September 2023

Key words: canopy, nutrients, water constraints, wine grapes

A long-term trial was conducted in commercial vineyards in the Coastal region of South Africa to assess the impact of treated municipal wastewater irrigation on vineyards. Cabernet Sauvignon and Sauvignon blanc grapevines were irrigated using treated municipal wastewater from the Potsdam wastewater treatment works for 11 years. Grapevines were either rainfed (RF), irrigated with treated municipal wastewater *via* a single dripper line (SLD) or received twice the volume of wastewater *via* a double dripper line (DLD). Grapevine responses were measured from the 2013/14 to 2017/18 seasons. Although high amounts of K^+, Na^+ and Cl^- were applied *via* wastewater irrigation, it did not result in excessive uptake by plants and did not affect vegetative growth or yield negatively. Irrigation reduced water constraints throughout the growing season compared to RF conditions, particularly for Cabernet Sauvignon. Consequently, SLD and DLD grapevines produced stronger vegetative growth and higher yields compared to RF. Results showed that the availability of irrigation water (albeit of relatively low quality) in regions where grapevines are usually grown under dryland conditions can increase grapevine productivity whilst maintaining good fruit quality. However, the water can vary in its availability as well as its quality over a short period of time. Plant and soil water status should be monitored regularly to avoid over-irrigation. Implementing low frequency irrigation scheduling with a sufficient leaching fraction will allow adequate time between irrigation applications for soils to aerate and organic material to decompose. Irrigation water, soils and grapevine leaves should be analysed to ensure that chemical parameters conform to recommended thresholds and norms.

INTRODUCTION

In recent years, the Western Cape province of South Africa experienced frequent water shortages and below-average rainfall that led to the worst drought the province has ever experienced (Botai *et al*., 2017). The ongoing drought was particularly detrimental to the wine industry as water constraints experienced during a particular season may impact grapevine growth and yield in the following seasons. As a result, water scarcity has become an increasingly important challenge to the agricultural sector in the region. Growers have had to improve their water use efficiency, irrigation techniques and scheduling (Myburgh, 2018). In areas that experienced severe water shortages, more profitable vineyards were prioritised and received more irrigation water and less profitable vineyards were removed.

Water restrictions imposed by the authorities and the limited supply of fresh water that can be stored on farms have emphasised the need for alternative irrigation water sources. Treated municipal wastewater has been used as an alternative source of irrigation water in many arid and semi-arid countries such as Israel (Levy *et al*., 2014), North America, Mexico and Australia (Laurenson *et al*., 2012). It has been found to be a suitable source of irrigation water in Mediterranean countries that have limited fresh water supplies during summer and high rainfall during winter. The latter can facilitate the leaching of salts applied *via* wastewater

[1]*The Fruit, Vine and Wine Institute of the Agricultural Research Council*

**Corresponding author: E-mail address: howellc@arc.agric.za*

Acknowledgements: This study formed part of Project K5/2561//4 which was initiated, managed and funded by the Water Research Commission (WRC), and co-funded by Winetech and the Agricultural Research Council (ARC). Messrs. Pierre Blake for permission to work in his vineyard, as well as the grapes used for samples and Egbert Hanekom for managing the vineyard and general assistance. Staff of the Soil and Water Science Division at ARC Infruitec-Nietvoorbij for technical support. The study formed part of Miss Karla Hoogendik's M.Sc. Agric. thesis

irrigation leading to sodicity. Approximately 2 000 ha of vineyards in the Swartland and surrounding regions are irrigated with treated municipal wastewater supplied by the City of Cape Town's Potsdam wastewater treatment works (WWTW) and the Malmesbury municipality (Myburgh, 2018). However, no studies have assessed the feasibility of using such wastewater for vineyard irrigation under South African conditions.

Using treated municipal wastewater for irrigation has various potential benefits and disadvantages which have been described previously (Hoogendijk, 2019; Hoogendijk *et al.*, 2023). In brief, it provides an additional source of irrigation water which can be used to improve vegetative growth and yield potential (Myburgh, 2018). Treated municipal wastewater often contains high amounts of macro-elements, therefore nutrients such as N, P and K^+ can be recycled if applied *via* the irrigation water. The presence of organic compounds in treated municipal wastewater may have positive effects on soil structural stability. On the negative side, municipal wastewater usually has high salt loads which can affect the physical, chemical and biological properties of the soil.

High concentrations of salts in municipal wastewater can influence the water relations and gas exchange of irrigated crops (Paranychianakis *et al.*, 2004). Salinity negatively affects the water absorption capacity of plants and could result in water stress (Gómez-Bellot *et al.*, 2015). Saline soil conditions can cause the accumulation of salts (primarily Na^+ & Cl^-) in the aerial parts of plants, which in turn can affect plant metabolic processes if ions are not compartmentalised within the cell vacuoles (Gómez-Bellot *et al.*, 2013). Plants adapt to these osmotic stresses by exercising osmotic adjustment which maintains a positive turgor that is required for the opening of stomata and cell enlargement (Álvarez *et al.*, 2012). Severe water losses are prevented by decreasing the aperture of stomata (Gómez-Bellot *et al.*, 2015). A study by Paranychianakis *et al.* (2004) investigating the effect of municipal wastewater irrigation on one-year-old Sultanina grapevines reported that midday stem water potential (Ψ_S) was unaffected by wastewater irrigation, but predawn leaf water potential (Ψ_{PD}) was reduced in comparison with grapevines irrigated with fresh water. The reduction was ascribed to the osmotic effect caused by the accumulation of salts in the root zone. The unaffected Ψ_S was considered to be due to the grapevines' isohydric behaviour which controls water use and helps maintain the minimum leaf water potential (Ψ_L) at a constant value (Winkel & Rambal, 1993; Paranychianakis *et al.*, 2004).

Using treated municipal wastewater as a source of N for plant production has been well documented (Rusan *et al.*, 2007; Chen *et al.*, 2013; Thapliyal *et al.*, 2013; Kamboosi, 2017). McCarthy (1981) showed that there were adequate levels of petiole N of Shiraz grapevines that were irrigated with treated municipal wastewater at a rate of 45 L of wastewater per grapevine per week compared to grapevines irrigated with 135 L potable water per grapevine per week. Neither of the treatments received additional N fertilisation. Furthermore, grapevines irrigated with 135 L wastewater per grapevine per week did not exhibit excessive vegetative growth nor did it reduce fruitfulness. Irrigation using municipal wastewater had no effect on the petiole N content of Riesling grapes when compared to grapevines irrigated with well water (Neilsen *et al.*, 1989). Greater K^+ accumulation was observed in petioles of Shiraz grapevines that were irrigated with fresh water compared to those irrigated with sewage effluent, even though the water sources had similar K^+ concentrations (McCarthy, 1981).

Although an increase in petiole Ca^{2+} levels for Riesling grapevine (Neilsen *et al.*, 1989) and Mg^{2+} as a response to irrigation with municipal wastewater irrigation has been reported (McCarthy, 1981), petiole concentrations of Mg^{2+} in Riesling grapes were lower for grapevines irrigated with municipal wastewater compared to those irrigated with well water (Neilsen *et al.*, 1989). This could possibly be due to a K-Mg antagonism within the plant where wastewater contained appreciable amounts of K^+. The uptake of Na^+ by plants as a result of municipal wastewater irrigation has been widely investigated (McCarthy, 1981; Koo & Zekri, 1989; Zekri & Koo, 1993; Kiziloglu *et al.*, 2008; Zavadil, 2009; Khaskoussy *et al.*, 2013; Netzer *et al.*, 2014; Bedbabis & Ferrara, 2018; Libutti *et al.*, 2018). There were greater accumulations of Na^+ in the xylem sap, trunk wood, bark and leaves of Superior Seedless grapevines irrigated with treated municipal wastewater compared to those irrigated with fresh water (Netzer *et al.*, 2014). Similar findings have been reported for Shiraz petioles (McCarthy, 1981).

High nutrient content (especially N & P) present in treated municipal wastewater can lead to an increase in the yield and biomass production of grapes under wastewater irrigation (Neilsen *et al.*, 1989; Mendoza-Espinosa *et al.*, 2008). In another study, the yield of grapevines irrigated with municipal wastewater was similar compared to that of grapevines irrigated with fresh water (McCarthy, 1981; Netzer *et al.*, 2014). This suggested that treated municipal wastewater may not adversely affect grapevine growth. Moreover, due to the nutrient supply through wastewater, similar yields could be obtained without the application of additional fertilisers. Therefore, the use of municipal wastewater for irrigation in water scarce regions may increase crop productivity substantially when no alternative or limited water sources are available.

Neilsen *et al.* (1989) reported an increase in must total soluble solids (TSS) and pH of Riesling grapes that were irrigated with treated municipal wastewater. However, total titratable acidity (TTA) was not affected, and it did not limit the production of high quality wine. There were no differences in the TSS, TTA and pH of Cabernet Sauvignon and Merlot grapes that were irrigated with either secondary treated municipal wastewater or groundwater (Mendoza-Espinosa *et al.*, 2008). Elevated concentrations of N, P, K^+, Na^+, Cl^- and Mg^{2+} and pH in wines produced from Shiraz grapes in response to irrigation with municipal wastewater have also been reported (McCarthy & Downton, 1981). In that particular study, wines produced from grapevines irrigated with wastewater also had higher anthocyanin and phenolic contents.

The objective of the study was to assess the effects of long-term irrigation with treated municipal wastewater on grapevine vegetative growth, yield and juice characteristics in the latter part of a field trial in commercial vineyards in the Coastal region of the Western Cape, South Africa. The low winter rainfall in 2017 in this particular region and the looming onset of drought and water restrictions highlighted the necessity for alternative sources of water for vineyard irrigation for the South African wine industry. Therefore, in the last season of the study, *i.e.* the 2017/20 season, grapevine plant water status, leaf chemical status and canopy characteristics were also measured.

MATERIALS AND METHODS

Site selection and vineyard characteristics

The field trial was carried out in commercial vineyards of a farm near the town of Philadelphia in the Western Cape (-33.401661°, 18.334810°) from flowering (November) in the 2006/07 season until dormancy (July) in the 2017/18 season. The farm is located 12.4 km from the Atlantic Ocean, situated *ca.* 130 m above sea level and has a mean February temperature (MFT) of 22.1°C (Myburgh, 2011). The region has a Mediterranean climate and is classified as a class III climatic region according to its growing degree days (GDD) from September to March (Winkler, 1974). Three experimental sites were selected in different landscape positions on the farm (Fig. 1). The first site was in a *Vitis vinifera* L. *cv*. Sauvignon blanc vineyard located on the shoulder of a hill. The second and third sites were in two *V. vinifera* L. *cv.* Cabernet Sauvignon vineyards situated on a backslope and a footslope, respectively (Table 1). Further details regarding soil characteristics as well as soil chemical and physical properties will be given in a subsequent article. All grapevines were planted on 99R rootstock. The grapevines were planted 2.75 m × 1.20 m and trained onto a moveable five strand lengthened Perold trellis. Vertical shoot positioning (VSP) was implemented to prevent the development of a sprawling canopy. The vineyard was managed according to the grower's normal viticultural practices in terms of cover crop and fertiliser management.

Irrigation treatments and application

The three main experimental sites were divided into three plots, each receiving a different irrigation treatment. Each of the treatment plots consisted of one row of 15 experimental grapevines, a buffer row of grapevines on each side and at least two buffer grapevines at each end of the experimental rows. The first treatment was rainfed (RF), *i.e.* farmed under dryland conditions. This was considered a control treatment given that no raw water was available for irrigation on the farm. The second treatment was drip irrigated with treated municipal wastewater *via* a single dripper line (SLD) on the grapevine row. Drippers were spaced 1 m apart and had a flow rate of 2.3 L/h. The volume of water applied, and the irrigation frequency was according to the grower's normal irrigation schedule. The third treatment had a double dripper line (DLD) which supplied double the volume of wastewater on the grapevine row. The three main experimental sites were irrigated separately according to the grower's irrigation schedule from the 2006/07 to the 2017/18 season. Water meters were installed in the dripper lines of the SLD plots at the beginning of the study period to measure irrigation volumes. The volumes of water applied to the DLD plots were calculated as twice the volume applied to the SLD plots for the respective landscape position. Irrigation commenced between September and November of each year until May or June of the next year, when the first winter rains fell. Irrigation volumes, as well as rainfall data were documented each month for the duration of the study period. Due to the measurement of irrigation volumes on a monthly basis, it was not possible to identify specific dates on which irrigation was applied. An assessment of the water quality and nutrient load of the treated municipal wastewater applied in the study was reported by Howell *et al*. (2022b).

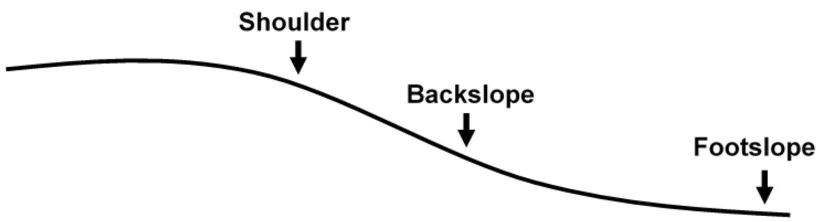

FIGURE 1.
Relative landscape positions of the experimental sites on a farm near Philadelphia.

TABLE 1
Vineyard characteristics of the experimental sites on a farm near Philadelphia.

Landscape position	Scion cultivar	Rootstock	Planting date
Shoulder	Sauvignon blanc	99R	2000
Backslope	Cabernet Sauvignon	99R	2002
Footslope	Cabernet Sauvignon	99R	2001

 DOI: https://doi.org/10.21548/44-2-5871

Soil water content

Soil water content (SWC) was measured once a month for the duration of the study using a calibrated neutron probe. One access tube (50 mm Ø class 4 Polyvinyl chloride [PVC]) was installed on the grapevine row at each of the treatment plots at the beginning of the study period using a 50 mm custom-built steel auger. Measurements were taken in 30 cm increments up to a depth of 90 cm. Before and after measurements, neutron count readings were recorded by taking five standard count readings while the probe was standing on the neutron probe case. Count ratios were calculated by determining the ratio between the actual neutron probe readings at each depth and the mean of the ten standard count readings (Moffat, 2017). Subsequently, the count ratios were calibrated against volumetric soil water content (θ_V).

To establish θ_V, gravimetric soil water content (θ_g) was determined by taking three replicate soil samples at each of the treatment plots on the same day as neutron probe readings. Soil samples were collected over the 0-30 cm, 30-60 cm and 60-90 cm soil layers with a Viehmeyer soil auger on the grapevine row close to the neutron probe access tubes. The sampled soils were placed in individual metal cans and sealed, whereafter the samples were weighed on a laboratory balance (Sartorius Excellence E2000D, Göttingen, Germany) at the ARC Infruitec-Nietvoorbij Irrigation laboratory. The samples were then oven-dried at 105°C for 16 hours in cans with their lids removed. Following this, the cans were removed from the oven, the cans were closed, and samples were placed in a desiccator containing copper sulfate ($CuSO_4$) crystals.

Once cooled down, samples were weighed again and θ_g was calculated using the following equation:

$$\theta_g = (m_w - m_d) \div m_d \quad \text{(Eq. 1)}$$

where m_w is the initial mass of wet soil in g, m_d is the mass of dried soil in g. The θ_g of each plot was determined as the mean of the three gravimetric samples. Subsequently, θ_V was calculated as follows:

$$\theta_V = \theta_g \text{ x } \rho_b \quad \text{(Eq. 2)}$$

where ρ_b is soil bulk density. A ρ_b of 1.65 g/cm^3 was used for the calculation, which is the mean ρ_b of over 70 soils in the Western Cape as determined by Van Huysteen (1989). Soil water content for each soil layer was calculated as follows:

$$SWC = \theta_V \text{ x d x } 100 \quad \text{(Eq. 3)}$$

where d is the depth of the soil layer (dm). The SWC for the respective soil layers were summed to obtain the SWC of the 90 cm soil profile.

Grapevine water status

Grapevine water potential was measured using the pressure chamber technique (Scholander *et al.,* 1965), according to guidelines described by Myburgh (2010) in the last season of the study. During the 2017/18 season, Ψ_S was measured at each treatment plot in three mature, unscathed leaves located opposite a bunch. The leaves were covered in aluminium foil bags (Choné *et al*., 2001; Myburgh, 2010) for a minimum of one hour before measurements were carried out (Howell, 2016). The mean Ψ_S per treatment at each of the landscape positions was calculated. Measurements were carried out at pea size (November 2017), véraison (December 2017) and prior to harvest (February 2018).

Vegetative grapevine measurements

Leaf chemical status

At véraison of the 2017/18 growing season, 30 mature leaves opposite a bunch were collected per treatment plot at each of the landscape positions. Petioles were immediately removed from the leaf blades and the leaves were placed into paper bags. The samples were then dried in a fan oven at 60°C for 24 hours. The chemical status of the dried leaf blades was determined by a commercial laboratory. Leaf N was determined according to the methods described by Horneck and Miller (1998) by means of a nitrogen analyser. An ICP-OES spectrometer (PerkinElmer Optima 7300 DV, Waltham, Massachusetts, U.S.A.) was used to determine P, K^+, Ca^{2+}, Mg^{2+}, Na^+, Cl^- Mn^{2+}, Fe^{2+}, Cu^{2+}, Zn^{2+} and B^{3+} according to methods described by Isaac and Johnson (1998).

Growth characteristics

During the 2017/18 ripening period, five grapevines were randomly selected per treatment plot from each of the three landscape positions (experimental sites) and one shoot per grapevine was collected (*i.e.* 5 × 9 = 45 shoots in total) to analyse canopy characteristics. Shoots were selected from spurs close to the crown of the grapevine. Shoots were cut off at the base, placed in plastic bags and transported to the laboratory for analyses. Secondary shoots were separated from the primary shoots. The length of primary and secondary shoots was measured, and the number of secondary shoots counted. The number of internodes on primary shoots was also counted. The average length of shoots and internodes per treatment was calculated for each of the treatment plots. The mean diameter of primary shoots was estimated by measuring the shoot diameter with a digital caliper at the top, middle and bottom of each shoot. Leaves were separated into primary and secondary leaves. Leaves were counted, and the total leaf area was measured using an electronic surface area meter (LI-COR Model 3100C, Nebraska, U.S.A.). Leaf area per grapevine (m^2) was calculated by multiplying the total leaf area per shoot by the number of shoots per grapevine. The leaf area index was calculated by dividing the leaf area per grapevine by the plant spacing (Mehmel, 2010).

Over the last four years of the study period, *i.e.* 2015 to 2018, grapevine vigour was quantified by measuring pruning mass in the dormant period (ARC, unpublished data). Cane mass was determined in the vineyard at each of the treatment plots after pruning using a hanging balance.

Yield and its components

At harvest in the 2013/14 to 2017/18 seasons, ten randomly selected bunches were picked from each treatment plot at the three landscape positions. The bunches were weighed using an electronic balance to determine bunch mass. A sample of 100 berries was obtained by picking ten berries from each of the ten bunches. The berry samples were weighed in the laboratory to determine the mean berry mass. All the bunches of the treatment plots were picked by hand and counted using a mechanical counter at harvest. The objective was to harvest the grapes at 24°B, but due to logistical constraints this was not always possible. A top loader mechanical balance was used to weigh the grapes and obtain the total mass per treatment plot. Grape mass per grapevine (kg/grapevine) was calculated by dividing the total grape mass per treatment by the number of grapevines per treatment which as then converted to yield (t/ha).

Grape juice characteristics

A representative sample of bunches was selected at harvest in the 2013/14 to 2017/18 seasons. Bunches were gently crushed to extract juice from the berries. The juice was poured through a fine sieve and collected in 50 mL sample tubes. The samples were analysed for TSS using a handheld refractometer (Atago PAL 1, Tokyo, Japan). The TTA and pH were determined at the Department of Viticulture and Oenology of Stellenbosch University using an automatic titrator (Metrohm 785 DMP Titrino, Herisau, Switzerland).

Statistical analysis

Since the primary objective of the study was to obtain a range of soil and grapevine responses to irrigation with treated municipal wastewater, it cannot be regarded as a comparative study. Therefore, there were no treatment replications. It must be noted that a number of vineyard field trials investigating soil and vineyard responses to irrigation have followed a similar approach (Bruwer, 2010; Mehmel, 2010; Howell *et al.*, 2022a). Calculations of means and standard deviations (SD) were carried out using Microsoft Office Excel 365 version. Due to the nature of the project, no statistical analyses of the data was initially planned. However, on discussions with statisticians, it became clear that would be possible to compare results obtained with the different irrigation strategies. In order to do this, the different seasons were considered as replications. The data was subjected to analysis of variance (Anova) using GLM (General Linear Models) Procedure of SAS software (Version 9.4; SAS Institute Inc, Cary, USA). Shapiro-Wilk test was performed on the standardized residuals from the model to test for deviation from normality. Fisher's least significant difference was calculated at the 5% level to compare treatment means. A probability level of 5% was considered significant for all significance tests.

RESULTS AND DISCUSSION

Soil water content

The SWC of the irrigated treatment plots (Fig. 2A) at the shoulder site was consistently higher than the RF plot, however, the SLD and DLD plots maintained relatively similar SWC throughout the 2017/18 growing season. Above average rainfall during August 2017 resulted in increased SWC for all of the RF treatments (Fig. 2A-C). The

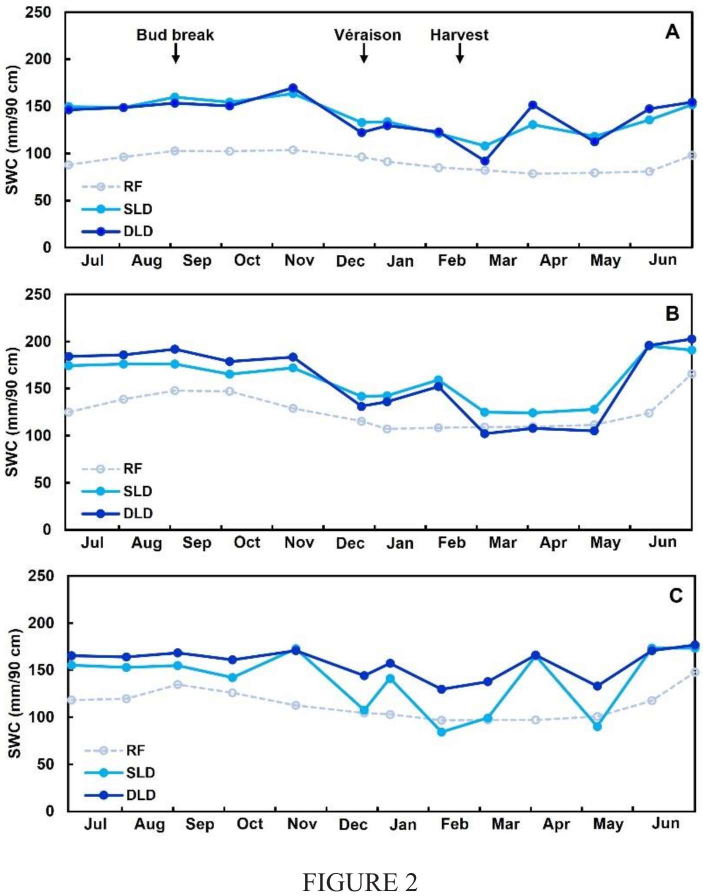

FIGURE 2

Effect of rainfed conditions (RF) and irrigation with treated municipal wastewater *via* single (SLD) and double line drip (DLD) on the soil water content (SWC) up to 90 cm soil depth of (A) a shoulder, (B) a backslope and (C) a footslope from July 2017 to June 2018.

first irrigation of the season was applied in November 2017 and would therefore explain the slightly increased SWC of the irrigated treatments during that particular period. The SWC at the shoulder site decreased progressively during the summer months until April 2018 when 20 mm of rainfall was recorded (Fig. 2A). Thereafter the winter rainfall period began which increased the SWC at all the experimental plots. Despite the higher clay content of the shoulder site, this landscape position had lower SWC compared to the backslope and footslope sites (Fig. 2A-C). This is likely a result of (i) the high stone fraction at the shoulder site (data not shown), which decreased the water holding capacity of the soil and (ii) the convex form of the landscape which facilitated the lateral movement of water through the soil to lower landscape positions.

The DLD plot at the backslope site had higher SWC compared to the SLD plot before the irrigation season commenced, whereafter it decreased to levels below what was measured at the SLD plot and only increased to similar SWC again in the winter of 2018 (Fig. 2B). Increased vegetative and reproductive growth under DLD irrigation would have increased the water requirements of grapevines and resulted in greater soil water depletion during the summer months compared to grapevines under SLD. No irrigation was applied at the backslope site during February and April 2018 (data not shown). This could explain the substantial decrease in SWC of the irrigated treatments at this site during the post-harvest period (Fig. 2B).

The SWC of the irrigated plots at the footslope site followed similar trends as observed at the backslope, but at lower levels of SWC (Fig. 2C). The SWC at the footslope site at the beginning of the season was 165 mm and 155 mm for the DLD and SLD treatment plots, respectively, whereas SWC values at the backslope site were 184 mm and 174 mm for the respective plots during the same time (Fig. 2A-C). The application of higher volumes of irrigation water at the footslope DLD plot was reflected by subtle changes in SWC throughout the season compared to the SLD plot which experienced more severe fluctuations in SWC (Fig. 2C). During the harvest period, the SWC of the footslope SLD plot decreased to levels below that of the RF plot. This was most likely due to strong vegetative growth and higher crop load which increased the grapevine water requirement and subsequently depleted soil water to 84 mm (Fig. 2C). Similar to the backslope site, no irrigation was applied at the footslope during April 2018, which would explain the substantial decrease in SWC of the irrigated plots in early May (Fig. 2C). The SWC of all the treatments increased steadily after May due to substantial rainfall during May and June 2018.

Grapevine water status

At pea size berry stage of the 2017/18 growing season, with the exception of the backslope DLD and footslope SLD plots, the irrigated treatments did not experience any water constraints according to thresholds for water stress levels proposed by Van Leeuwen *et al*. (2009) for Sauvignon blanc and Myburgh *et al*. (2016) for Cabernet Sauvignon grapevines (Fig. 3A-C). However, grapevines at the RF plots experienced low water constraints at the shoulder and backslope and moderate constraints at the footslope site during this growth stage (Fig. 3A-C). On 18 December 2017 (véraison), all of the grapevines at the shoulder site experienced moderate water constraints, with Ψ_S varying between -0.9 MPa and -1.1 MPa (Fig. 3A). In contrast, the grapevines of the RF plot at the backslope site were already experiencing severe water constraints (Fig. 3B). Prior to harvest, there was little difference between the treatments and all the grapevines experienced severe water constraints, with the exception of the grapevines at the footslope DLD plot (Fig. 3C). According to water constraint thresholds, the maximum Ψ_S measured at the footslope DLD plot fell under Class IV, namely "high water constraints", which is regarded as ideal to produce quality Cabernet Sauvignon wine on a clay soil (Myburgh *et al*., 2016). The substantially higher Ψ_S measured at the footslope DLD plot during véraison and harvest was most probably a result of the high volumes of irrigation water applied at this plot (Howell *et al*., 2022b) and subsequent greater SWC (Fig. 3C). At the back- and footslope sites, the Ψ_S was consistently higher at the SLD and DLD plots when compared to the RF plots, albeit very slightly (Fig. 3B-C). Similarly, Mehmel (2010) reported lower Ψ_S in non-irrigated grapevines when compared to grapevines irrigated with SLD and DLD in the Swartland and attributed this to greater SWC in irrigated plots. From the results of the current study, it is clear that irrigation with treated municipal wastewater was only beneficial in preventing water constraints up until véraison, whereafter irrigated grapevines experienced similar levels of water stress compared to non-irrigated grapevines. Similar results were reported by Intrigliolo and Castel (2008) for Tempranillo grapevines under RF and irrigated conditions during seasons with limited rainfall.

Vegetative grapevine measurements

Leaf chemical status

Chemical analysis of the leaf blades at véraison of the 2017/18 season revealed that all of the experimental grapevines had levels of N exceeding the recommended norms of 1.5% to 2.4% (Conradie, 1994). No substantial differences were observed between treatment plots. However, leaf N content tended to increase slightly with the amount of irrigation water applied (Table 2). Given that the N content of the leaves was above the recommended norm of 2.4%, care should be taken to avoid over-fertilisation that could lead to excessive vegetative growth and reduced fruitfulness (Saayman, 1981 and references therein). The leaf blade P content (Table 2) of all of the grapevines was within the recommended range of 0.12% to 0.45% (Conradie, 1994), except for slightly higher concentrations in the shoulder SLD, DLD and footslope DLD plots. According to Paranychianakis *et al*. (2006), irrigation with treated municipal wastewater significantly increased the leaf P concentrations of Sultanina grapevines when compared to grapevines irrigated with fresh water.

The leaf blade K^+, Ca^{2+} and Mg^{2+} concentrations (Table 2) of all of the experimental grapevines were within the recommended norms (Conradie, 1994). Furthermore, no trends were observed that could be related to the different irrigation treatments. In contrast, Neilsen *et al*. (1989) reported increased K^+ and Ca^{2+} and decreased Mg^{2+} levels in

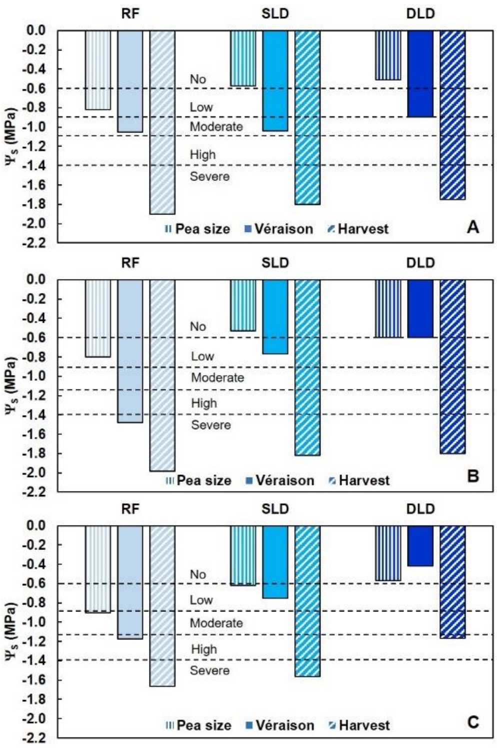

FIGURE 3
Effect of rainfed conditions (RF) and irrigation with treated municipal wastewater *via* single (SLD) and double line drip (DLD) on the midday stem water potential (Ψ_S) in (A) Sauvignon blanc on a shoulder and Cabernet Sauvignon on (B) a backslope and (C) a footslope at pea size, véraison and harvest during the 2017/18 season.

the petioles of Riesling grapevines as a result of municipal wastewater irrigation. Leaf petiole Mg^{2+} of Shiraz grapevines increased when municipal wastewater was used for irrigation rather than fresh water (McCarthy, 1981).

Although high amounts of Cl^- were applied *via* wastewater irrigation (Howell *et al.*, 2022b), leaf blade Cl^- concentrations (Table 2) in all of the treatment plots were below the recommended threshold value of 0.5% (Beyers, 1962; Christensen, 2005). There was no clear trend relating to the irrigation treatments (Table 2). Similarly, although high amounts of Na^+ were applied *via* the irrigation with treated municipal wastewater (Howell *et al.*, 2022b), no trend was observed with regard to the leaf blade Na^+ content (Table 2). In addition, leaf blade Na^+ concentrations were well below the recommended threshold value of 0.25% (Conradie, 1994). This indicated that grapevines did not accumulate excessive amounts of Na^+ when irrigated with treated municipal wastewater. Conversely, Netzer *et al*. (2014) reported significantly greater Na^+ concentrations in the leaf petioles of table grapes (*Vitis vinifera* L. *cv*. Superior Seedless) under treated municipal wastewater irrigation when compared to grapevines irrigated with fresh water and supplied with fertiliser. Furthermore, petiole Na^+ increased with an increasing amount of irrigation water applied.

Growth characteristics

Canopy characteristics

Prior to the harvest of the 2017/18 season, the Sauvignon blanc grapevines in the shoulder RF plot showed slight visual water constraints (Hoogendijk, 2019), *i.e.* light green leaves and a less dense canopy compared to the irrigated treatment plots. This was to be expected as the grapevines in this plot experienced severe water constraints at harvest with Ψ_S reaching -1.9 MPa (Fig. 3A). In addition, the SWC of the 0-90 cm soil layer of the RF plot was below 90 mm prior to harvest (Fig. 2A). The SLD and DLD treatment plots at the shoulder site experienced similar levels of water constraints at harvest, *i.e.* Ψ_S of -1.8 and -1.75, respectively. However, almost no visual symptoms of water stress were observed at these grapevines. Furthermore, the grapevine canopy of the SLD plot appeared to be denser than that of the DLD plot. The occurrence of actively growing shoots prior to harvest in irrigated Cabernet Sauvignon grapevines near Philadelphia has been reported previously (Mehmel, 2010). This growth is undesirable since active vegetative growth during the ripening period may become a strong sink that competes with reproductive growth (Smart & Robinson, 1991).

Visual water constraints in the form of yellowing basal leaves in the bunch zone (Hoogendijk, 2019) were observed in all the treatment plots on the backslope site prior to harvest of the 2017/18 season. The Ψ_S measured at harvest was similar between the plots and ranged between -1.80 MPa and -1.98 MPa which indicated severe water constraints (Fig. 3B). Furthermore, grapevines in the backslope SLD and DLD plots had denser canopies when compared to the RF plot. This is most likely due to the greater SWC of the irrigated treatments (Fig. 2B).

Only the grapevines of the RF plot showed visual signs

 DOI: https://doi.org/10.21548/44-2-5871

TABLE 2
Nutrient status of Sauvignon blanc leaves on a shoulder, as well as Cabernet Sauvignon leaves on a backslope and footslope, respectively, at véraison during the 2017/18 season.

Landscape position	Treatment	N (%)	P (%)	K^+ (%)	Ca^{2+} (%)	Mg^{2+} (%)	Cl^- (%)	Na^+ (mg/kg)	B^{3+} (mg/kg)	Cu^{2+} (mg/kg)	Fe^{2+} (mg/kg)	Mn^{2+} (mg/kg)	Zn^{2+} (mg/kg)
Shoulder	RF	2.89	0.38	0.98	1.39	0.54	0.14	888	57	8	215	323	47
	SLD	2.94	0.56	0.90	1.66	0.52	0.19	918	59	7	204	350	52
	DLD	2.95	0.70	1.01	1.66	0.55	0.14	966	62	8	262	425	62
Backslope	RF	2.63	0.29	1.02	1.57	0.34	0.08	1089	95	8	506	161	44
	SLD	2.92	0.44	0.93	1.72	0.32	0.03	866	76	8	248	275	49
	DLD	3.12	0.35	0.73	1.94	0.36	0.09	763	73	11	210	232	39
Footslope	RF	2.65	0.29	1.12	1.97	0.33	0.10	703	71	9	199	233	43
	SLD	2.90	0.36	0.81	1.50	0.25	0.07	701	60	8	237	243	46
	DLD	3.01	0.48	1.02	1.80	0.32	0.12	873	67	10	247	243	55

of water constraints at the footslope site. This could be explained by both low SWC (Fig. 2C) and low Ψ_S (Fig. 3C) measured in this particular plot during the harvest period. The canopy in the bunch zone of the DLD plot was visibly denser than that of the SLD plot. This is likely due to considerably higher Ψ_S (Fig. 3) and SWC (Fig. 2C) at harvest. Excessive shade in the bunch zone of Cabernet Sauvignon grapevines in Stellenbosch resulted in reduced berry mass, bunch mass, yield and skin colour and increased the K^+ concentration, pH and TTA of the grape must (Archer & Strauss, 1989). Densely shaded canopies may also increase the chances of developing Botrytis bunch rot and induce unwanted herbaceous characters in wine (Smart *et al*., 1990 and references therein). Since Cabernet Sauvignon is considered to be a vigorous, low yielding cultivar (Goussard, 2008), it is particularly sensitive to over-irrigation (Bruwer, 2010).

With the exception of the grapevines at the backslope site, the length of the primary shoots tended to expand (Table 3) with an increase in the amount of irrigation water applied (Howell *et al.*, 2022b). Similar results were reported for Cabernet Sauvignon grapevines in the Swartland region (Mehmel, 2010). Shoots shorter than 30 cm produced berries that were low in sugar and phenol concentrations and were poorly coloured, whereas 1.2 m shoots were considered optimal for producing high quality Cabernet Sauvignon grapes (Mehmel, 2010 and references therein). Therefore, the SLD irrigated grapevines exhibited optimal shoot growth since the length of primary shoots varied between 1.11 m and 1.31 m (Table 3). In contrast, the primary shoots of the shoulder and footslope DLD treatment plots were 1.5 m and longer, indicating excessive vegetative growth.

The DLD plot at the footslope site also had substantially more and longer secondary shoots (Table 3). When compared to rainfed and severely stressed grapevines, drip irrigated Cabernet Sauvignon grapevines had increased vigour and active shoot growth during the ripening period which induced competition for photosynthetic assimilates and reduced berry sugar content (Tandonnet *et al*., 1999). The elongation of primary shoots was associated with an increase in the length of internodes.

In addition, the primary shoot diameter of the Cabernet Sauvignon grapevines increased with an increase in irrigation rates (Table 3). Although this response was not observed for the Sauvignon blanc grapevines at the shoulder site, the number of primary leaves per shoot increased with the amount of irrigation water applied. This was also observed at the Cabernet Sauvignon grapevines of the footslope site. However, the number of secondary leaves per primary shoot did not follow a clear trend at any of the experimental sites. Similarly, the total number of leaves per primary shoot remained largely unaffected by irrigation water application at the shoulder and backslope sites, whereas the footslope site exhibited a slight increase in the number of leaves as the amount of irrigation water increased (Table 3).

The leaf area per grapevine of the Cabernet Sauvignon grapevines increased with the amount of irrigation water applied (Table 4). Similarly, the leaf area of the Sauvignon blanc grapevines at the shoulder site was greater for the irrigated treatments when compared to the RF plot, but little difference could be seen between the SLD and DLD plots (Table 4). The SLD plot had a slightly higher leaf area index (LAI) compared to the DLD plot (Fig. 4). The grapevine LAI in the backslope site increased with the amount of irrigation water applied. The grapevines of the footslope DLD plot had excessively high leaf area per grapevine which was also reflected by the LAI (Fig. 4). This could result in reduced bud fertility and fruit of poorer quality (Smart *et al*., 1990).

TABLE 3
Mean vegetative growth components of Sauvignon blanc grapevines on a shoulder and Cabernet Sauvignon grapevines on a backslope and footslope, respectively, under rainfed conditions (RF) and irrigated with treated municipal wastewater via single (SLD) or double line drip (DLD) during the ripening period of the 2017/18 season.

		RF	SLD	DLD
Cultivar	**Landscape position**	**Primary shoot length (m)**		
Sauvignon blanc	Shoulder	0.79	1.31	1.52
Cabernet Sauvignon	Backslope	0.52	1.11	1.07
Cabernet Sauvignon	Footslope	0.76	1.27	1.67
		Primary shoot internode length (mm)		
Sauvignon blanc	Shoulder	8.06	8.49	8.56
Cabernet Sauvignon	Backslope	8.81	10.77	12.75
Cabernet Sauvignon	Footslope	9.47	9.90	11.25
		Primary shoot diameter (mm)		
Sauvignon blanc	Shoulder	6.85	6.55	6.76
Cabernet Sauvignon	Backslope	5.99	8.18	8.59
Cabernet Sauvignon	Footslope	5.26	5.95	6.86
		Number of primary leaves per shoot		
Sauvignon blanc	Shoulder	17	25	34
Cabernet Sauvignon	Backslope	9	13	10
Cabernet Sauvignon	Footslope	13	18	28
		Secondary shoot length (m)		
Sauvignon blanc	Shoulder	0.12	0.11	0.08
Cabernet Sauvignon	Backslope	0.08	0.10	0.10
Cabernet Sauvignon	Footslope	0.06	0.17	0.16
		Number of secondary shoots		
Sauvignon blanc	Shoulder	9	19	18
Cabernet Sauvignon	Backslope	2	5	8
Cabernet Sauvignon	Footslope	5	2	13
		Number of secondary leaves per shoot		
Sauvignon blanc	Shoulder	58	96	82
Cabernet Sauvignon	Backslope	11	21	32
Cabernet Sauvignon	Footslope	21	16	79
		Total number of leaves per shoot		
Sauvignon blanc	Shoulder	50	51	56
Cabernet Sauvignon	Backslope	31	34	30
Cabernet Sauvignon	Footslope	32	52	59

Cane mass

Irrigation using treated municipal wastewater increased the cane mass of grapevines compared to the RF control (Fig. 5, Table 5). These results were expected since the irrigated plots had higher SWC for most of the season (Fig. 2), as well as higher Ψ_S (Fig. 3). Similar results were reported for irrigated and non-irrigated Cabernet Sauvignon grapevines in the Swartland region (Mehmel, 2010). In the Coastal region, cane mass for Sauvignon blanc grapevines in soil with higher SWC was higher when compared to grapevines in drier soil in the same vineyard (Conradie *et al*., 2002). According to Williams (2000), reduced shoot growth is one of the first visible symptoms of grapevine water constraints. In this regard, the availability of treated municipal wastewater

 DOI: https://doi.org/10.21548/44-2-5871

TABLE 4
Mean leaf area of Sauvignon blanc grapevines on a shoulder and Cabernet Sauvignon grapevines on a backslope and footslope, respectively, under rainfed conditions (RF) and irrigated with treated municipal wastewater *via* single (SLD) or double line drip (DLD) during the ripening period of the 2017/18 season.

		RF	SLD	DLD
Cultivar	**Landscape position**	**Primary leaf area per shoot (m^2)**		
Sauvignon blanc	Shoulder	0.15	0.21	0.32
Cabernet Sauvignon	Backslope	0.06	0.14	0.11
Cabernet Sauvignon	Footslope	0.10	0.18	0.25
		Secondary leaf area per shoot (m^2)		
Sauvignon blanc	Shoulder	0.23	0.43	0.29
Cabernet Sauvignon	Backslope	0.03	0.09	0.12
Cabernet Sauvignon	Footslope	0.07	0.07	0.45
		Total leaf area per shoot (m^2)		
Sauvignon blanc	Shoulder	0.38	0.64	0.61
Cabernet Sauvignon	Backslope	0.09	0.22	0.23
Cabernet Sauvignon	Footslope	0.17	0.25	0.70
		Total leaf area per grapevine (m^2)		
Sauvignon blanc	Shoulder	7.73	13.69	12.45
Cabernet Sauvignon	Backslope	2.32	6.76	8.54
Cabernet Sauvignon	Footslope	5.47	8.18	24.30

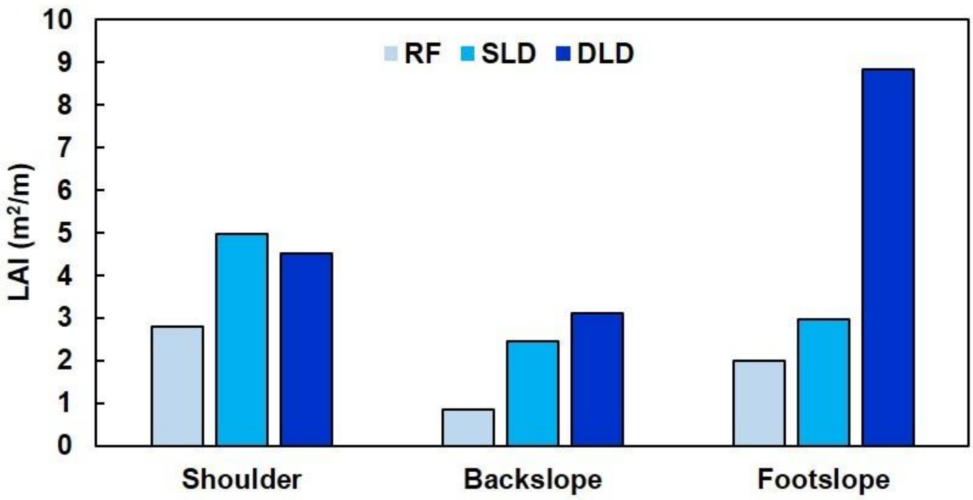

FIGURE 4
Leaf area index (LAI) of Sauvignon blanc grapevines on a shoulder and Cabernet Sauvignon grapevines on a backslope and footslope, respectively, under rainfed conditions (RF) and irrigated with treated municipal wastewater *via* single (SLD) and double line drip (DLD) during the ripening period of the 2017/18 season.

as an irrigation water source had a positive impact on grapevine vegetative growth in a region where grapevines are traditionally grown under RF conditions due to a lack of natural freshwater resources. Except for the footslope RF plot, the cane mass measured during the 2017/18 season was greater at all of the treatment plots when compared to the mean cane mass of the previous three seasons (Fig. 5). This was likely a result of larger volumes of irrigation water applied at the SLD and DLD plots compared to the 2013/14, 2014/15 and 2015/16 seasons (Hoogendijk, 2019). The foregoing suggests that irrigation with treated municipal wastewater did not pose a salinity hazard to grapevine vegetative growth.

Yield and its parameters

Irrigation with treated municipal wastewater increased bunch mass substantially at all three experimental sites during the 2017/18 season (Table 6). At the shoulder and backslope sites, the increased bunch mass was associated with larger berries for the irrigated treatments, whereas the SLD and DLD plots of the footslope site had larger berries as well as more bunches per grapevine compared to the RF plot (Table 6). Although the irrigated treatments increased the bunch mass substantially at the shoulder and backslope sites when compared to the RF plots, the additional irrigation water applied *via* the DLD did not result in a higher bunch mass compared to the SLD plots (Table 6). In contrast, the bunch mass of the Cabernet Sauvignon grapes at the footslope increased with the amount of irrigation water applied (Fig. 2B & Table 6). This could be explained by the amount of irrigation water applied at this site throughout the season (Howell *et al.*, 2022b) and the subsequent lower water constraints experienced at the DLD plot (Fig. 3). Mirás-Avalos and Intrigliolo (2017) reported that the berry mass of Sauvignon blanc grapes was severely reduced when Ψ_S became more negative. Berries are most sensitive to water deficits during the beginning stages of berry development and berry size could be reduced (Williams, 2000). Water

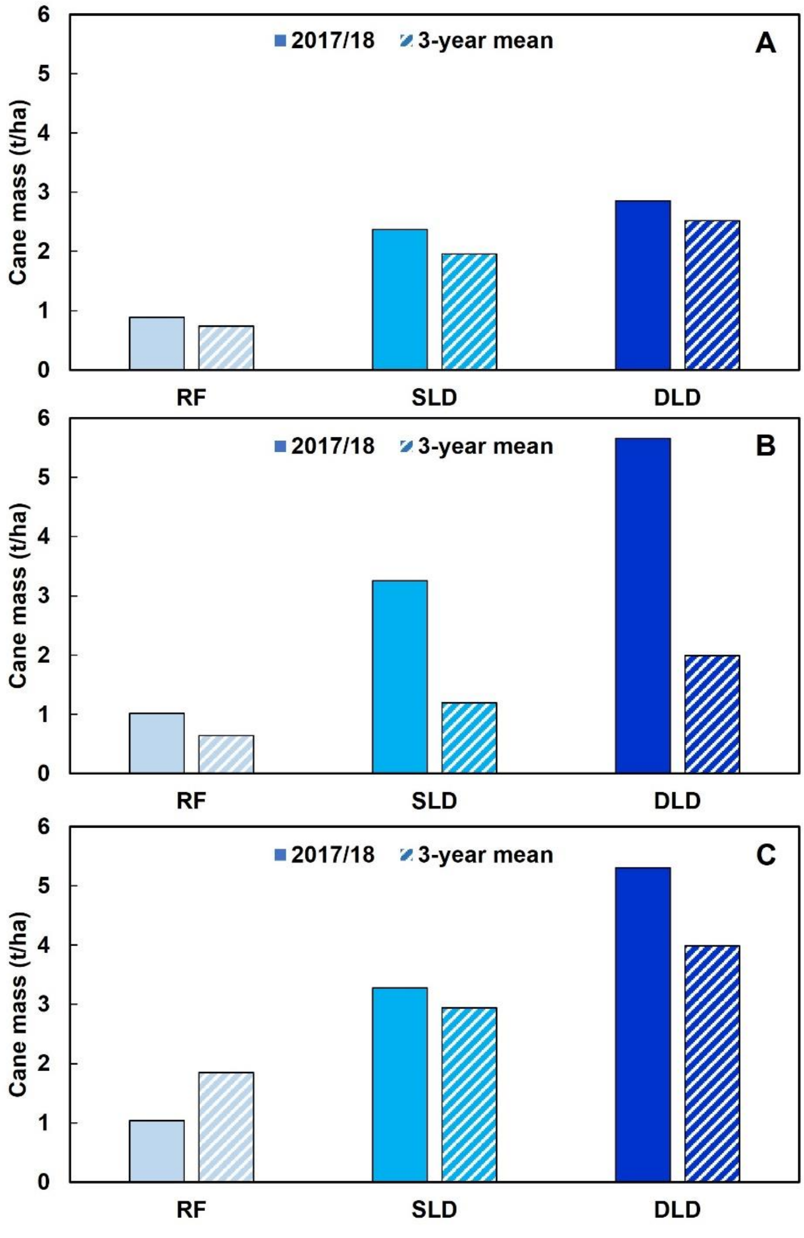

FIGURE 5
Effect of rainfed conditions (RF) and irrigation with treated municipal wastewater *via* single (SLD) and double line drip (DLD) on the cane mass in (A) Sauvignon blanc on a shoulder and Cabernet Sauvignon on (B) a backslope and (C) a footslope during the 2017/18 season compared to the mean for the 2014/15 to the 2016/17 season.

 DOI: https://doi.org/10.21548/44-2-5871

constraints prior to véraison can result in smaller berries (Van Leeuwen *et al*., 2004). High water constraints that were associated with low soil matric potential during the period from flowering to harvest reduced the berry size of Cabernet Sauvignon grapevines in the Swartland region (Mehmel, 2010). In the Lower Olifants River region, berries of 0.78 g were measured for Cabernet Sauvignon grapevines growing on sandy soil and irrigated according to a deficit irrigation strategy (Bruwer, 2010). Similarly, water deficits experienced by Shiraz grapevines between flowering and véraison reduced berry size irreversibly (Ojeda *et al*., 2001). Water constraints during the period from flowering to berry set may reduce the number of berries that set (Hardie & Considine, 1976).

Irrigation with treated municipal wastewater increased grapevine yield in all of the treatment plots compared to the RF control (Fig. 6A-C, Table 7). During the 2017/18 season, yield followed similar trends to bunch mass. Therefore, the increased yield can be attributed to bigger bunches in the irrigated treatments. Similar to bunch mass, the yield between the SLD and DLD treatment plots of the shoulder and backslope sites did not differ substantially, whereas the yield at the footslope site increased with an increasing amount of irrigation water applied (Fig. 6). Similar results were reported for Cabernet Sauvignon grapevines in the Swartland region (Mehmel, 2010). Shiraz grapevines irrigated with 135 L of municipal wastewater per week had more and heavier bunches, which resulted in greater yields compared to grapevines irrigated with either 45 L of municipal wastewater per week or 135 L of fresh water per week (McCarthy, 1981). Similar to what was found for cane mass, results confirmed that irrigation with treated municipal wastewater did not pose a salinity hazard to yield. Low rainfall during the beginning stages of berry development (data not shown) might help to explain the lower yields measured at the RF treatments compared to the mean yield of the previous four seasons (Fig. 6A-C). The higher yield measured at the footslope DLD plot is probably a result of

TABLE 5
Mean cane mass of Sauvignon blanc grapevines on a shoulder and Cabernet Sauvignon grapevines on a backslope and footslope, respectively, under rainfed conditions (RF) and irrigated with treated municipal wastewater *via* single (SLD) or double line drip (DLD).

Cultivar	Landscape position	RF	SLD	DLD
		Cane mass (t/ha)		
Sauvignon blanc	Shoulder	0.77 c[1]	2.05 b	2.59 a
Cabernet Sauvignon	Backslope	0.76 a	1.88 a	3.21 a
Cabernet Sauvignon	Footslope	1.65 b	3.03 ab	4.31 a

(1) Values designated by the same letters within a row do not differ significantly ($p \leq 0.05$).

TABLE 6
Yield components of Sauvignon blanc grapevines on a shoulder and Cabernet Sauvignon grapevines on a backslope and footslope, respectively, under rainfed conditions (RF) and irrigation with treated municipal wastewater via single (SLD) and double line drip (DLD) during the 2017/18 season.

Cultivar	Landscape position	RF	SLD	DLD
		Berry mass (g)		
Sauvignon blanc	Shoulder	1.34	1.85	1.88
Cabernet Sauvignon	Backslope	0.46	1.11	0.94
Cabernet Sauvignon	Footslope	0.55	0.94	1.19
		Bunch mass (g)		
Sauvignon blanc	Shoulder	91	153	150
Cabernet Sauvignon	Backslope	29	94	134
Cabernet Sauvignon	Footslope	23	95	82
		Number of bunches per grapevine		
Sauvignon blanc	Shoulder	24	27	28
Cabernet Sauvignon	Backslope	43	37	46
Cabernet Sauvignon	Footslope	24	32	36

high irrigation volumes applied at this plot (Hoogendijk., 2019).

Juice characteristics

Juice TSS of the Sauvignon blanc grapes at the shoulder site was not affected by the different irrigation treatments, whereas the RF treatment plots of the Cabernet Sauvignon grapevines at the backslope and footslope sites had slightly higher TSS compared to the irrigated treatments (Fig. 7A-C; Table 8). This is likely a result of actively growing shoots and excessive vegetative growth at the SLD and DLD treatment

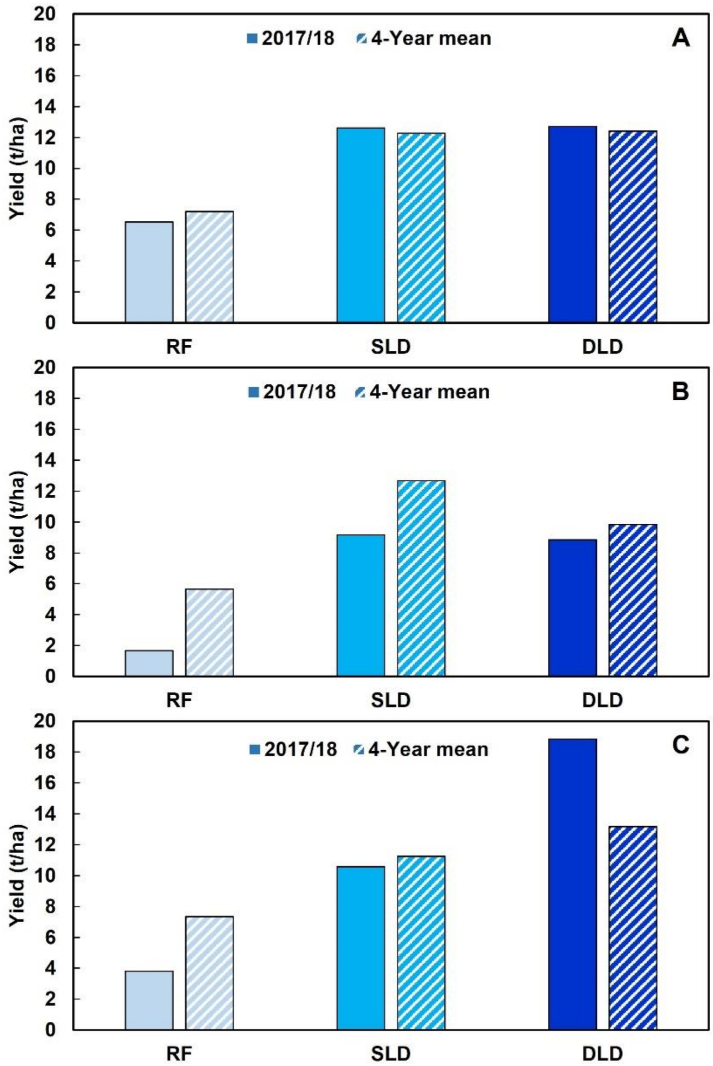

FIGURE 6

Effect of rainfed conditions (RF) and irrigation with treated municipal wastewater *via* single (SLD) and double line drip (DLD) on the yield in (A) Sauvignon blanc on a shoulder, as well as Cabernet Sauvignon on (B) a backslope and (C) a footslope during the 2017/18 season compared to the mean for the 2013/14 to the 2016/17 season.

TABLE 7

Mean yield of Sauvignon blanc grapevines on a shoulder and Cabernet Sauvignon grapevines on a backslope and footslope, respectively, under rainfed conditions (RF) and irrigated with treated municipal wastewater *via* single (SLD) or double line drip (DLD).

		RF	SLD	DLD
Cultivar	Landscape position	Yield (t/ha)		
Sauvignon blanc	Shoulder	7.06 b[(1)]	12.34 a	12.48 a
Cabernet Sauvignon	Backslope	4.86 b	9.65 a	11.98 a
Cabernet Sauvignon	Footslope	6.63 b	11.11 a	14.30 a

[(1)] Values designated by the same letters within a row do not differ significantly ($p \leq 0.05$).

DOI: https://doi.org/10.21548/44-2-5871

plots during the ripening period which was a stronger sink for photosynthates compared to the ripening grapes (Mehmel, 2010). The higher yields of the irrigated treatments may also have obstructed sugar accumulation due to sink competition (Kliewer & Dokoozlian, 2005). Since all the Cabernet Sauvignon grapes had to be harvested on the same day (due to logistical reasons), the RF plots probably accumulated more sugars over the ripening period. It has been reported previously that grapevine water constraints enhance berry sugar content in low yielding grapevines, whereas it reduces the berry sugar content of high yielding grapevines (Van Leeuwen *et al*., 2009 and references therein). The 2017/18 TSS followed similar trends to the mean of the previous four seasons (Fig. 7A-C).

The TTA of the Cabernet Sauvignon grapes at the back- and footslope sites increased with the amount of irrigation water applied (Fig. 8B-C; Table 8). The lower TTA measured at the RF treatment plots may be a result of increased sunlight penetration in the less dense bunch zone which lead to more berry exposure and reduced TTA (Iland, 1989; Conradie *et al*., 2002). The increase in TTA with increased water application can also be related to less water constraints experienced by the grapevines at the SLD and DLD plots during the ripening period (Fig. 3B-C). Mehmel (2010) reported reduced TTA in non-irrigated Cabernet Sauvignon grapevines compared to grapevines irrigated *via* a single or double dripper line. The reduction in TTA was attributed to water constraints experienced during the ripening period as well as the warm climate of the Swartland region. In contrast, the TTA of the Sauvignon blanc grapes at the shoulder site did not differ between the RF and SLD plots, however, TTA was higher for the the DLD plot (Fig. 8A; Table 8). These results were expected as the RF and SLD plots at the shoulder site experienced similar water constraints during the ripening period (Fig. 3A). Similar results were reported by Conradie *et al*. (2002) for Sauvignon blanc grapes in the Coastal region where lower acidity and higher pH was observed for grapevines planted in a Glenrosa soil as a result of water stress. The TTA measured during the 2017/18 season followed similar trends to the mean TTA of the previous four seasons (Fig. 8A-C).

The different irrigation treatments did not affect the juice pH at harvest of either the Sauvignon blanc or Cabernet Sauvignon grapes during the 2017/18 season (Fig. 9A-C). Similar results were seen for the mean juice pH of the previous four seasons. With the exception of the RF plots of the back-

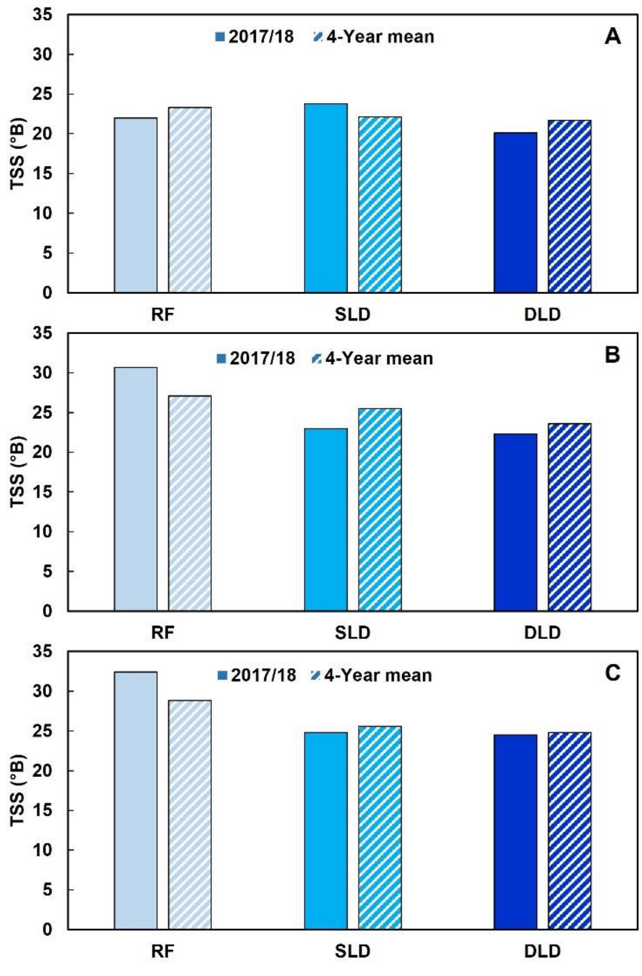

FIGURE 7

Effect of rainfed conditions (RF) and irrigation with treated municipal wastewater *via* single (SLD) and double line drip (DLD) on the grape juice total soluble solids (TSS) in (A) Sauvignon blanc on a shoulder, as well as Cabernet Sauvignon on (B) a backslope and (C) a footslope during the 2017/18 season compared to the mean for the 2013/14 to the 2016/17 season.

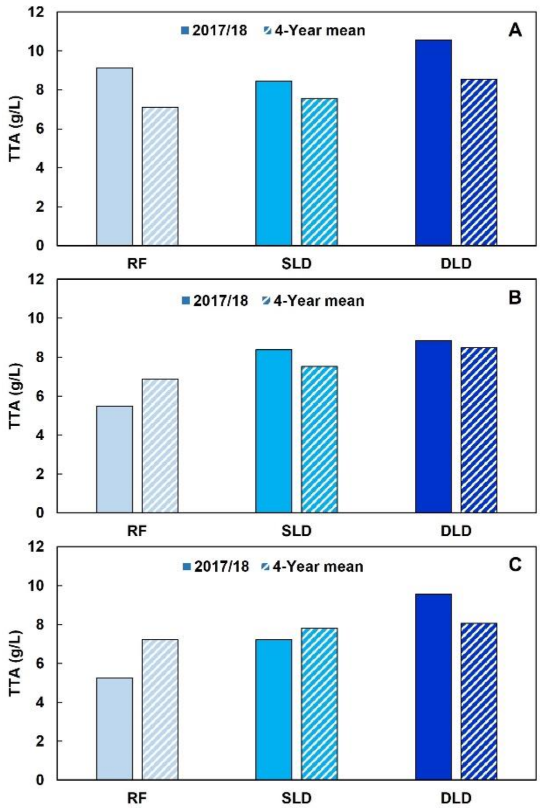

FIGURE 8
Effect of rainfed conditions (RF) and irrigation with treated municipal wastewater *via* single (SLD) and double line drip (DLD) on total titratable acidity (TTA) in (A) Sauvignon blanc on a shoulder, as well as Cabernet Sauvignon on (B) a backslope and (C) a footslope during the 2017/18 season compared to the mean for the 2013/14 to the 2016/17 season.

and footslope sites, juice pH was within the range of 3.0 to 3.8 recommended by Kodur (2011). High juice pH (*e.g.* > 3.8) is often associated with high juice K^+ concentrations which may result in wines with poor colour stability and taste (Somers, 1975). Previous studies have linked increased berry K^+ concentrations to increased K^+ supply to grapevines (Morris *et al*., 1983; Ruhl, 1989). McCarthy and Downton (1981) reported increased pH in wines made from Shiraz grapes that received 135 L of municipal wastewater per week compared to those irrigated with the same amount of fresh water. The increased pH was attributed to greater K^+ concentrations and resulted in wines with poor colour, less anthocyanins and a greater "chemical age". Despite the high amounts of K^+ applied *via* treated municipal wastewater irrigation during this study, no detrimental effects with regard to juice quality were observed (Table 8). In fact, irrigation tended to improve the quality of the must compared to the RF control treatments.

CONCLUSIONS

Although high amounts of K^+, Na^+ and Cl^- were applied *via* wastewater irrigation, it did not result in excessive uptake by plants and did not negatively affect vegetative growth or yield. This suggested that grapevines possess mechanisms to regulate the uptake of ions from the soil solution. Despite the high amounts of salts applied *via* treated municipal wastewater irrigation, no salinity hazards with regard to vegetative growth and yield were observed for the irrigated treatments. The irrigation reduced water constraints throughout the growing season compared to RF conditions, particularly in the case of Cabernet Sauvignon. Consequently, the SLD and DLD grapevines produced stronger vegetative growth and higher yields compared to RF grapevines. Results showed that the availability of irrigation water (albeit of relatively low quality) in regions where grapevines are usually grown under dryland conditions can increase productivity of grapevines whilst maintaining good fruit quality.

It should be noted that municipal wastewater can vary in its availability. The generation of treated municipal wastewater may also decrease during periods of drought when the use of potable water is restricted. This is important to consider when planning an irrigation strategy. Furthermore, the quality of the wastewater can vary greatly over a short period of time. During droughts, the concentrations of inorganic chemical constituents in treated municipal wastewater may increase due to the restricted use of potable water. Although this study indicated that grapevines can be irrigated successfully using treated municipal wastewater, proper management is required to limit possible negative effects on grapevines and the environment. It is therefore recommended to monitor plant and soil water status regularly, and by doing so, avoid over-irrigation. Implementing low frequency irrigation scheduling with a sufficient leaching fraction will allow adequate time between irrigation applications for soils to

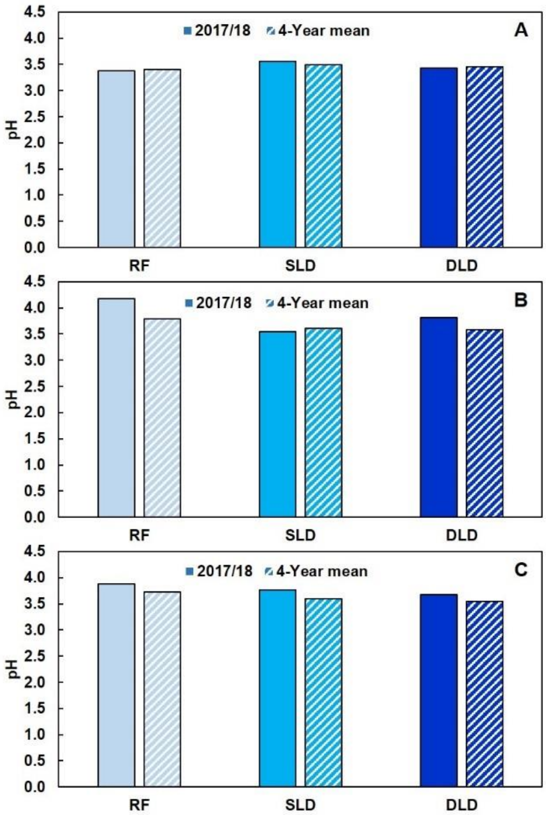

FIGURE 9
Effect of rainfed conditions (RF) and irrigation with treated municipal wastewater *via* single (SLD) and double line drip (DLD) on the grape juice pH in (A) Sauvignon blanc on a shoulder, as well as Cabernet Sauvignon on (B) a backslope and (C) a footslope during the 2017/18 season compared to compared to the mean for the 2013/14 to the 2016/17 season.

TABLE 8
Mean total soluble solids, total titratable acidity and juice pH of Sauvignon blanc grapevines on a shoulder and Cabernet Sauvignon grapevines on a backslope and footslope, respectively, under rainfed conditions (RF) and irrigated with treated municipal wastewater *via* single (SLD) or double line drip (DLD).

		RF	SLD	DLD
Cultivar	**Landscape position**	**Total soluble solids (°B)**		
Sauvignon blanc	Shoulder	23.00 a	22.46 a	21.4 a
Cabernet Sauvignon	Backslope	27.82 a	25.02 b	23.32 b
Cabernet Sauvignon	Footslope	29.49 a	25.40 b	24.72 b
		Total titratable acidity (g/L)		
Sauvignon blanc	Shoulder	7.51 b	7.73 b	8.95 a
Cabernet Sauvignon	Backslope	6.60 b	7.69 ab	8.54 a
Cabernet Sauvignon	Footslope	6.82 a	7.69 a	8.36 a
		pH		
Sauvignon blanc	Shoulder	3.41 a	3.49 a	3.45 a
Cabernet Sauvignon	Backslope	3.79 a	3.61 a	3.58 a
Cabernet Sauvignon	Footslope	3.72 a	3.60 ab	3.55 b

(1) Values designated by the same letters within a row do not differ significantly ($p \leq 0.05$).

aerate and organic material to decompose. This will also have the advantage of leaching excess salts beyond the root zone and thereby preventing potential problems associated with salinity and infiltration. If infiltration is negatively affected, the application of a surface mulch may help to restore structural stability at the soil surface. Routine analysis of irrigation water, soils and grapevine leaves is also recommended when irrigating with wastewater to ensure that chemical parameters conform to recommended thresholds and norms. This can help to prevent irreversible damage to irrigation equipment, soils and grapevines. Furthermore, grapevines should be monitored for deficiency and toxicity symptoms of trace elements that could accumulate in soils and grapevines under wastewater irrigation.

LITERATURE CITED

Álvarez, S., Gómez-Bellot, M.J., Castillo, M., Bañón, S. & Sánchez-Blanco, M.J., 2012. Osmotic and saline effect on growth, water relations, and ion uptake and translocation in *Phlomis purpurea* plants. Environ. Exp. Bot. 78, 138-145.

Archer, E. & Strauss, H.C., 1989. Effect of shading on the performance of *Vitis vinifera* L. *cv*. Cabernet Sauvignon. S. Afr. J. Enol. Vitic. 10, 74-76.

Bedbabis, S. & Ferrara, G., 2018. Effects of long term irrigation with treated wastewater on leaf mineral element contents and oil quality in Olive cv. Chemlali. J. Hortic. Sci. Biotechnol. 93, 216-223.

Beyers, E., 1962. Diagnostic leaf analysis for deciduous fruit. S. Afr. J. Agric. Sci. 5, 315-329.

Botai, C.M., Botai, J.O., De Wit, J.P., Ncongwane, K.P. & Adeola, A.M., 2017. Drought characteristics over the Western Cape Province, South Africa. Water 9, 876.

Bruwer, R.J., 2010. The edaphic and climatic effects on production and wine quality of Cabernet Sauvignon in the Lower Olifants River region. Thesis, Stellenbosch University, Private Bag X1, 7602 Matieland (Stellenbosch), South Africa.

Chen, W., Lu, S., Jiao, W., Wang, M. & Chang, A.C., 2013. Reclaimed water: A safe irrigation water source? Environ. Dev. 8, 74-83.

Choné, X., Van Leeuwen, C., Durbourdieu, D. & Gaudillére, J.P., 2001. Stem water potential is a sensitive indicator of grapevine water status. Ann. Bot. 87, 477-483.

Christensen, P., 2005. Use of tissue analysis in viticulture. In: Proc. Varietal Winegrape Production Short Course, University of California Davis, U.S.A., March 2005, pp. 1-9.

Conradie, W.J., 1994. Vineyard fertilisation. Proceedings of workshop on vineyard fertilization. Nietvoorbij, 30 September 1994. ARC Infruitec-Nietvoorbij, Private Bag X5026, 7599 Stellenbosch, South Africa.

Conradie, W.J., Carey, V.A., Bonnardot, V., Saayman, D. & Van Schoor, L.H., 2002. Effect of different environmental factors on the performance of Sauvignon blanc grapevines in the Stellenbosch/Durbanville districts of South Africa. I. Geology, soil, climate, phenology and grape composition. S. Afr. J. Enol. Vitic. 23, 78-91.

Gómez-Bellot, M.J., Álvarez, S., Castillo, M., Bañón, S., Ortuño, M.F. & Sánchez-Blanco, M.J., 2013. Water relations, nutrient content and developmental responses of *Euonymus* plants irrigated with water of different degrees of salinity and quality. J. Plant Res. 126, 567-576.

Gómez-Bellot, M.J., Nortes, P.A., Ortuño, M.F., Romero, C., Fernández-García, N. & Sánchez-Blanco, M.J., 2015. Influence of arbuscular mycorrhizal fungi and treated wastewater on water relations and leaf structure alterations of *Viburnum tinus* L. plants during both saline and recovery periods. J. Plant Physiol. 188, 96-105.

Goussard, P.G., 2008 (1st ed). Grape cultivars for wine production in South Africa (in Afrikaans). Cheviot Publishing, Cape Town, South Africa.

Hardie, W.J. & Considine, J.A., 1976. Response of grapes to water-deficit stress in particular stages of development. Am. J. Enol. Vitic. 27, 55-61.

Hoogendijk, K., 2019. Soil and grapevine responses to irrigation with treated municipal and winery wastewaters. Thesis, Stellenbosch University, Private Bag X1, 7602 Matieland (Stellenbosch), South Africa.

Hoogendijk, K., Myburgh, P.A., Howell. C.L. & Hoffman, J.E., 2023. Irrigation of agricultural crops with municipal wastewater - A review. S. Afr. J. Enol. Vitic. 44, 31-54.

Horneck, D.A. & Miller, R.O., 1998. Determination of total nitrogen in plant tissue. In: Kalra, Y.P. (ed). Handbook of reference methods for plant analysis, CRC Press, Boca Raton. pp. 81-83.

Howell, C.L., 2016. Using diluted winery effluent for irrigation of *Vitis vinifera* L. *cv.* Cabernet Sauvignon and the impact thereof on soil properties with special reference to selected grapevine responses. Dissertation, Stellenbosch University, Private Bag X1, 7602 Matieland (Stellenbosch), South Africa.

Howell, C.L., Myburgh, P.A. & Hoogendijk, K., 2022a. Use of winery wastewater as a resource for irrigation of vineyards in different environments. WRC Report No. 2651/1/22. ISBN 978-0-6392-0341-6.

Howell, C.L., Hoogendijk, K., Myburgh, P.A. & Lategan, E.L., 2022b. An assessment of treated municipal wastewater used for irrigation of grapevines with respect to water quality and nutrient load. S. Afr. J. Enol. Vitic. 43, 168-179.

Iland, P., 1989. Grape berry composition- The influence of environmental and viticultural factors. Part 2: Solar radiation. Aust. Grapegrow Winem. April, 74-76.

Intrigliolo, D.S. & Castel, J.R., 2008. Effects of irrigation on the performance of grapevine cv. Tempranillo in Requena, Spain. Am. J. Enol. Vitic. 59, 30-38.

Isaac, R.A. & Johnson, W.C., 1998. Elemental determination by inductively coupled plasma. In: Kalra, Y.P. (ed). Handbook of reference methods for plant analysis, CRC Press, Boca Raton. pp. 165-170.

Kamboosi, K., 2017. The assessment of treated wastewater quality and the effects of mid-term irrigation on soil physical and chemical properties (case study: Bandargaz-treated wastewater). Appl. Water Sci. 7, 2385-2396.

Khaskhoussy, K., Hachicha, M., Kahlaoui, B., Messoudi-Nefzi, B., Rejeb, A., Jouzdan, O. & Arselan, A., 2013. Effect of treated wastewater on soil and corn crop in the Tunisian area. J. Appl. Sci. Res. 9, 132-140.

Kiziloglu, F.M., Turan, M., Sahin, U., Kuslu, Y. & Dursun, A., 2008. Effects of untreated and treated wastewater irrigation on some chemical properties of cauliflower (*Brassica olerecea* L. var. botrytis) and red cabbage (*Brassica olerecea* L. var. rubra) grown on calcareous soil in Turkey. Agric. Water Manage. 95, 716-724.

Kliewer, W.M. & Dokoozlian, N.K., 2005. Leaf area/crop weight ratios of grapevines: Influence on fruit composition and wine quality. Am. J. Enol. Vitic. 56, 170-181.

Kodur, S., 2011. Effects of juice pH and potassium on juice and wine quality, and regulation of potassium in grapevines through rootstocks (*Vitis*): A short review. Vitis 50, 1-6.

Koo, R.C.J. & Zekri, M., 1989. Citrus irrigation with reclaimed municipal wastewater. Proc. Fla. State Hort. Soc. 102, 51-56.

Laurenson, S., Bolan, N.S., Smith, E. & McCarthy, M., 2012. Review: Use of recycled wastewater for irrigating grapevines. Aust. J. Grape Wine Res. 18, 1-10.

Levy, G.J., Fine, P., Goldstein, D., Azenkot, A., Zilberman, A., Chazan, A. & Grinhut, T., 2014. Long term irrigation with treated wastewater (TWW) and soil sodification. Biosyst. Eng. 128, 4-10.

Libutti, A., Gatta, G., Gagliardi, A., Vergine, P., Pollice, A., Beneduce, L., Disciglio, G. & Tarantino, E., 2018. Agro-industrial wastewater reuse for irrigation of a vegetable crop succession under Mediterranean conditions. Agric. Water Manage. 196, 1-14.

McCarthy, M.G., 1981. Irrigation of grapevines with sewage effluent. I. Effects on yield and petiole composition. Am. J. Enol. Vitic. 32, 189-196.

McCarthy, M.G. & Downton, W.J.S., 1981. Irrigation of grapevines with sewage effluent. II. Effects on wine composition and quality. Am. J. Enol. Vitic. 32, 197-199.

Mehmel, T.O., 2010. Effect of climate and soil water status on Cabernet Sauvignon (*Vitis vinifera* L.) grapevines in the Swartland region with special reference to sugar loading and anthocyanin biosynthesis. Thesis, Stellenbosch University, Private Bag X1, 7602 Matieland (Stellenbosch), South Africa.

Mendoza-Espinosa, L.G., Cabello-Pasini, A., Macias-Carranza, V., Daessle-Heuser, W., Orozco-Borbón, M.V. & Quintanilla-Montoya, A.L., 2008. The effect of reclaimed wastewater on the quality and growth of grapevines. Water Sci. Technol. 57, 1445-1450.

Mirás-Avalos, J.M. & Intrigliolo, D.S., 2017. Grape composition under abiotic constrains: Water stress and salinity. Front. Plant. Sci. 8, 1-8.

Moffat, E.G., 2017. Mulching and tillage with compost to improve poor performing grapevines. Thesis, Stellenbosch University, Private Bag X1, 7602 Matieland (Stellenbosch), South Africa.

Morris, J.R., Sims, C.A. & Cawthon, D.L., 1983. Effects of excessive potassium levels on pH, acidity and color of fresh and stored grape juice. Am. J. Enol. Vitic. 34, 35-39.

Myburgh, P.A., 2010. Practical guidelines for the measurement of water potential in grapevine leaves. Winetech Technical Yearbook 2010, 11-13.

Myburgh, P.A., 2011. Determining the contribution of soil water status and selected atmospheric variables on water constraints in grapevines. Project WW13/14, Final report to Winetech, Vinpro building, Cecilia Street, 7646 Southern Paarl, South Africa.

Myburgh, P. A., 2018 (1st ed). Handbook for irrigation of wine grapes in South Africa. Agricultural Research Council, Pretoria, South Africa.

Myburgh, P.A., Cornelissen, R.J. & Southey, T.O., 2016. Interpretation of stem water potential measurements. Wineland June, 78-80.

Neilsen, G.H., Stevenson, D.S. & Fitzpatrick, J.J., 1989. The effect of municipal wastewater irrigation and rate of N fertilization on petiole composition, yield and quality of Okanagan Riesling grapes. Can. J. Plant. Sci. 69, 1285-1294.

Netzer, Y., Shenker, M. & Schwartz, M., 2014. Effects of irrigation using treated wastewater on table grape vineyards: Dynamics of sodium accumulation in soil and plant. Irrig. Sci. 32, 283-294.

Ojeda, H., Deloire, A. & Carbonneau, A., 2001. Influence of water deficits on grape berry growth. Vitis 40, 3, 141-145.

Paranychianakis, N.V., Chartzoulakis, K.S. & Angelakis, A.N., 2004. Influence of rootstock, irrigation level and recycled water on water relations and leaf gas exchange of Soultanina grapevines. Environ. Exp. Bot. 52, 185-198.

Paranychianakis, N.V., Nikolantonakis, M., Spanakis, Y. & Angelakis, A.N., 2006. The effect of recycled water on the nutrient status of Soultanina grapevines grafted on different rootstocks. Agric. Water Manage. 81, 185-198.

Ruhl, E.H., 1989. Effect of potassium and nitrogen supply on the distribution of minerals and organic acids and the composition of grape juice of Sultana vines. Aust. J. Exp. Agric. 29, 133-137.

Rusan, M.J.M., Hinnawi, S. & Rousan, L., 2007. Long term effect of wastewater irrigation of forage crops on soil and plant quality parameters. Desalination 215, 143-152.

Saayman, D., 1981. Grapevine nutrition (in Afrikaans). In: Burger, J.D. & Deist, J. (eds). Wingerdbou in Suid-Afrika. ARC Infruitec-Nietvoorbij, Private Bag X5026, 7599 Stellenbosch, South Africa.

Scholander, P.F., Hammel, H.T., Bradstreet, E.D. & Hemmingsen, E.A., 1965. Sap pressure in vascular plants. Science 148, 339-346.

Smart, R.E., Dick, J.K., Gravett, I.M. & Fisher, B.M., 1990. Canopy management to improve grape yield and wine quality- Principles and practices. S. Afr. J. Enol. Vitic. 11, 13-17.

Smart, R.E. & Robinson, M., 1991. Sunlight into wine. In: Handbook for winegrape canopy management. Winetitles, Australia.

Somers, T.C., 1975. In search of quality for red wines. Food Technol. Aust. 27, 49-56.

Tandonnet, J.P., Ollat, N., Neveux, M. & Renoux, J.L., 1999. Effect of three levels of water supply on the vegetative and reproductive development of Merlot and Cabernet Sauvignon grapevines. In: Rühl, E.H. & Schmid, J. (eds). Proc. 1st ISHS Workshop on water relations of grapevines., May 1998, Stuttgart, Germany. Acta Hort. 493, 301-307.

Thapliyal, A., Vasudevan, P., Dastidar, M.G., Tandon, M. & Mishra, S., 2013. Effects of irrigation with domestic wastewater on productivity of green chili and soil status. Commun. Soil Sci. Plant Anal. 44, 2327-2343.

Van Huyssteen, L., 1989. Quantification of the compaction problem of selected vineyard soils and a critical assessment of methods to predict soil bulk density from soil texture. Dissertation, Stellenbosch University, Private Bag X1, 7602 Matieland (Stellenbosch), South Africa.

Van Leeuwen, C., Friant, P., Choné, X., Tregoat, O., Koundouras, S. & Dubourdieu, D., 2004. Influence of climate, soil, and cultivar on terroir. Am. J. Enol. Vitic. 55, 207-217.

Van Leeuwen, C., Tregoat, O., Choné, X., Bois, B., Pernet, D. & Gaudillère, J.P., 2009. Vine water status is a key factor in grape ripening and vintage quality for red Bordeaux wine. How can it be assessed for vineyard management purposes? J. Int. Sci. Vigne Vin 43, 121-134.

Williams, L.E., 2000. Grapevine water relations. In: Raisin production manual. University of California, Agriculture & Natural Resources Publication 3393, Oakland, California, pp. 121-126.

Winkel, T. & Rambal, S., 1993. Influence of water stress on grapevines growing in the field: From leaf to whole-plant response. Aust. J. Plant Physiol. 20, 143-157.

Winkler, A.J., 1974. General viticulture. University of California Press, Los Angeles.

Zavadil, J., 2009. The effect of municipal wastewater irrigation on the yield and quality of vegetables and crops. Soil Water Res. 4, 91-103.

Zekri, M. & Koo, R.C.J., 1993. A reclaimed water citrus irrigation project. Proc. Fla. State Hort. Soc. 106, 30-35