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Post-veraison deficit irrigation regimes enhance berry coloration and health-promoting bioactive compounds in 'Crimson Seedless' table grapes

María R. Conesa[a], Natalia Falagán[b], José M. de la Rosa[a], Encarna Aguayo[b], Rafael Domingo[a], Alejandro Pérez Pastor[a],*

[a] Technical University of Cartagena (UPCT), Department of Plant Production, Paseo Alfonso XIII, 48. ETSIA. 30203, Cartagena (Murcia), Spain
[b] UPCT, Department of Food Engineering, Postharvest and Refrigeration Group, Paseo Alfonso XIII, 48, 30203 Cartagena (Murcia), Spain

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ABSTRACT

The impact of different post-veraison deficit irrigation regimes on yield, berry coloration and bioactive compounds in a commercial vineyard of 'Crimson Seedless' cv. was evaluated during three consecutive years (2011–2013). Four irrigation treatments were assayed: (i) a Control, irrigated at 110% of seasonal crop evapotranspiration (ETc), (ii) regulated deficit irrigation (RDI) irrigated similar to Control levels during pre-veraison and at 50% of the same during post-veraison (a non-critical period); (iii) partial root drying-zone (PRD), irrigated in a similar way to RDI but alternating (every 10–14 days) the dry and wet sides of the root-zone, and (iv) a null irrigation treatment (NI) which only received natural precipitation and occasional supplementary irrigation when the midday stem water potential (Ψ_s) exceeded −1.2 MPa. Total yield and fruit quality at harvest were not significantly affected by RDI or PRD. Only NI led to a reduction in yield and the weight of clusters and berries to compare with the other irrigated counterparts. All deficit irrigation treatments enhanced berry coloration and provided a higher crop yield in the first pick harvest compared with the Control treatment. Although RDI and PRD received similar annual volumes of water, PRD induced a greater accumulation of skin anthocyanins and resveratrol, while increasing the soluble phenolic content and antioxidant capacity evaluated at harvest. However, the higher values of anthocyanins observed in PRD could not be explained by higher values of xylem abscisic acid (ABA_{xylem}) because is the phloem which feeds berries during veraison.. Overall, our results demonstrate a strong relationship between the total amount of water supplied during the growing season and the main parameters related to yield, water use efficiency and bioactive compounds that are beneficial to health.

1. Introduction

New table grape cultivars (*Vitis vinifera* L.) with a commercial high value are constantly appearing because "seedlessness" has stimulated consumer acceptance worldwide. Approximately 80% of Spanish seedless table grapes are produced in warm-climate of the southeast of the country, where the red-table cv. 'Crimson Seedless' is one of the most important from an economic point of view. Its characteristic red peel is a consequence of the accumulation of anthocyanins in cells. However, reaching a commercially acceptable red color is problematic, probably because of the high summer temperatures which prevent proper color development (Peppi et al., 2006; Ferrara et al., 2014). Some early studies reported that flavonols stabilize the anthocyanin molecule through co-pigmentation (Singh Brar et al., 2008). Thus, both anthocyanins and flavonols belong to phenolic compounds. They are known to have antioxidant capacity and, in this sense, they have beneficial effects on human health. Antioxidant compounds are able to protect cells from oxidative stress, reducing the effects of neurodegenerative disease such as Alzheimer's (Dixon

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Abbreviations: DI, deficit irrigation; Control, full irrigation; RDI, regulated deficit irrigation; PRD, partial rootzone drying; NI, null irrigation; T, temperature; VPD, vapour pressure deficit; ET_0, reference crop evapotranspiration; kc, crop coefficient; ET_c, crop evapotranspiration; TSS, total soluble solids; TA, titratable acidity; EC, electrical conductivity; L*, lightness; C*, chrome; °h, hue angle; SPC, soluble phenolic content; GAE, gallic acid equivalent; TAC, total antioxidant capacity; AsAE, ascorbic acid equivalent; ABA_{xylem}, xylem abscisic acid; S-ABA, exogenous abscisic acid; Ψ_s, midday stem water potential; θ_v, soil volumetric water content; WUE, water use efficiency; WA, amount of water applied; Y_r, total relative yield; WA, rrelative amount of water applied.

* Corresponding author. Fax: +34 968 325793.
E-mail address: alex.perez-pastor@upct.es (A.P. Pastor).

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and Pasinetti, 2010) and helping to prevent cardiovascular diseases. Some studies also mention their anti-inflammatory activities and anticarcinogenic effects (Doshi et al., 2015). In particular, resveratrol, one of the most important phenolic compound present in grapes, has shown anti-atherosclerosis, anticoronary diseases and anticancer properties, which make it a particularly attractive food ingredient for human health (Flamini et al., 2013). Moreover, flavonols may also show antidiabetic activity (Doshi et al., 2015). Therefore, knowledge of the total antioxidant capacity (TAC) and phenolic profile is essential to health-promoting compounds.

Besides, it is known that the hormone abscisic acid found in the xylem (ABA_{xylem}) is accumulated in grape skins at the same time as anthocyanins and other phenolic compounds also increase (Coombe and Hale, 1973), although they have little effect on total soluble solids (TSS) or titratable acidity (TA) (Peppi et al., 2006).

Environmental constraints and cultural practices have a greater influence on the phenolic compostion and anthocyanins (Flamini et al., 2013). For example, soil water availability has been described as one of the most important constrains limiting grape production and fruit quality (Williams and Matthews, 1990). One way to counter water shortages is to apply deficit irrigation (DI) strategies, among which regulated deficit irrigation (RDI) and partial root-zone drying (PRD) have been the most commonly assessed. RDI, as defined by Chalmers et al. (1981), is based on reducing irrigation during certain periods of the growth cycle when the crops have low sensitivity to water stress. In the case of table grapes, a water deficit is generally applied after veraison, the onset of maturation, since reductions in irrigation before veraison can promote a smaller berry size and lower yield (Conesa et al., 2015). The application of RDI to table grapes decreases water usage with little or no impact on crop yield (Blanco et al., 2010; Faci et al., 2014), although, to date, the management of RDI has been driven by the need to control vine vigour and maximise fruit quality rather than the need to improve vineyard water use efficiency (Edwards and Clingeleffer, 2013). PRD is a variation of DI that requires approximately half of the root system to be maintained in a dry state, while the remainder of the root system is irrigated (Dry et al., 1996). The key point behind PRD is to expose part of the root system to the drying soil, leading the roots in this dry part to produce a signal so that the remaining roots in the wetted soil can maintain the water supply of the crop (Kang and Zhang, 2004). PRD also depends on the fact that root-to-shoot signalling (especially ABA_{xylem}) regulates the plant response to drying soil (Stoll et al., 2000). A comparison between PRD and RDI in grapevines reported little or no improvement in crop yield and fruit quality when PRD was used rather then RDI (Romero et al., 2012, 2014). The mechanism involved in the differential yield responses of PRD and RDI were reviewed by Dodd (2009), but no studies have looked at the impact of PRD and RDI on the yield and bioactive compounds of table grapes. The hypothesis is that a controlled water stress applied during post-veraison can improve berry coloration in red-varieties by increasing the bioactive compounds accumulation involved in the berry-ripening process (Peppi et al., 2007). The exogenous application of abscisic acid (S-ABA) is being investigated as a novel strategy to improve the quality of grapes (Ferrara et al., 2013, 2014). Although S-ABA is commonly sprayed on developing clusters to stimulate berry coloration, changes in root-to-shoot ABA_{xylem} signalling induced by variations in soil moisture dynamics may affect berry quality and bioactive compounds.

For these reasons, a 3-year long experiment was carried out on table grapes to (i) determine the effects of different post-veraison DI strategies on yield components, fruit quality and the bioactive compounds involved in the berry-ripening process; and (ii) compare the agronomical response of table grapes to PRD with that observed under a conventional RDI strategy.

2. Materials and methods

2.1. Site description and experimental design

The experiment was conducted over three consecutive years (2011–2013) at a commercial vineyard (*Vitis vinifera* L.) of 10-year-old 'Crimson Seedless' vines grafted onto Paulsen 1103 (4 × 4 m spacing) located in Cieza (Murcia, SE Spain). The experimental field conditions are described in detail in Conesa et al. (2015). Daily meteorological variables (T, temperature; RH, relative humidity; and Prec, precipitation) were recorded by an automatic weather station (CI42-www.siam.es) near the experimental site. The air vapor pressure deficit (VPD) was calculated each day using T and RH data. Daily reference crop evapotranspiration (ET_0) was computed according to the FAO-56 Penman–Montheith equation (Allen et al., 1998). Crop evapotranspiration (ET_c) was determined weekly from the product of ET_0 and the crop coefficient or kc (between 0.2 and 0.8), as proposed by Williams et al. (2003).

Four irrigation treatments were assessed: (i) a control treatment (Control) irrigated to satisfy maximum crop water requirements (ETc-110%) throughout the whole growing season; (ii) a RDI treatment, irrigated as the Control except post-veraison, when the vines were irrigated at 50% of the level used for the Control; (iii) a PRD treatment, irrigated as RDI (the same amount of water) but alternating the dry and wet sides of the root-zone every 10–14 days, when 75% of the soil field capacity (≈34% determined as gravimetric sample) was reached in the dry root-zone; and (iv) a null irrigation (NI) treatment, which received only rain water and additional irrigations when daily measured midday stem water potential (Ψ_s) was more negative than the established threshold value of −1.2 MPa (Conesa et al., 2012).

The experimental layout was a randomized complete block design with four block-replicates per irrigation treatment. Each replicate consisted of three adjacent rows of vines with six vines per row. The four central vines of the central row were monitored, while the others served as guard vines. A total of 288 vines were involved in this experiment. The vines were fertilised with 105–98–207 kg ha^{-1} year^{-1} of N, P_2O_5 and K_2O, respectively. Canopy management and standard cultural practices included girdling, pruning (based on leaving 8–10 spurs per vine), weed control, and the exogenous applications of S-ABA were the same for all the vines of the experiment, and were carried out by the technical department of the commercial orchard following usual criteria for the area. During the three post-veraison seasons assayed, two applications of S-ABA of 2 L ha^{-1} were sprayed on clusters of the whole experiment to enhance coloration of the berries as well to increase the amount of harvestable clusters at the first pick. This effect was evident and significant in all treatments after 48 h.

2.2. Vines and soil water status

Midday stem water potential (Ψ_s) was determined every 7–10 days from June to November on six sunny leaves per irrigation treatment (two leaves per replicate of three replications) with a Scholander-type chamber (Soil Moisture Equipment Corp. Model 3000, CA, USA) following the recommendations of Hsiao (1990). For Ψ_s determination (from 12.30 h to 13.30 h GMT), selected mature leaves near the trunk were wrapped in small black polyethylene bags and covered with silver foil at least 2 h prior to measurement. Soil volumetric water content (θ_v) was measured from 10 cm down to a maximum depth of 1 m every 0.1 m with a frequency domain reflectometry (FDR) probe (Diviner 2000®, Sentek Pty. Ltd., South Australia). The effective root depth was 0–50 cm because the soil layer below 60 cm was mainly hard clay (Conesa et al., 2014). Four access tubes (1 per replicate) were installed within the emitter