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A deficit irrigation strategy for 'Solar eclipse' plum in semi-arid climates

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Highlights

- Water scarcity drives testing of DI in semi-arid regions.
- Compared irrigation for plum yield, *WUE*, fruit quality, and physiological markers.
- DI cut yield 16% but doubled *WUE*, boosted stress markers, and lowered costs by 22%.
- The DI offers sustainable way to balance yield, quality, *WUE*.

Abstract: Water scarcity in semi-arid regions demands irrigation strategies that enhance water use efficiency (*WUE*) without compromising crop productivity. This study evaluated 'Solar Eclipse' plum (*Prunus salicina* L.) production under two irrigation regimes at El Tahadi Road, Nubaryia, Egypt: control irrigation (CI), supplying 100% of crop evapotranspiration (ET_c), and regulated deficit irrigation (DI), applying 50% ET_c from March to June. Trees under CI achieved the highest yield (16,250 kg·ha^{-1}), favouring markets focused on high-volume production. However, DI reduced yield by only 16% (13,650 kg·ha^{-1}) while significantly improving fruit quality, including higher total soluble solids (15.8 °Brix[1]), phenolic content (45.6 mg GAE·g^{-1}), and antioxidant capacity (82.6 μmol Trolox·g^{-1}). The DI treatment also nearly doubled *WUE* and lowered production costs by 22%, enhancing resource efficiency and economic sustainability. Biochemical analysis revealed increased leaf levels of proline, abscisic acid, and anthocyanins under DI, indicating activation of stress-responsive mechanisms that maintained fruit development despite reduced

[1] 1°Brix = 1 g of sucrose in 100 g of solution

water availability. Correlation analysis suggested DI enhanced *WUE* and fruit quality through physiological and biochemical adaptations, albeit with a modest yield reduction. Overall, this study emphasised the trade-offs between maximising yield and improving fruit quality, positioning regulated deficit irrigation as a viable, sustainable approach for 'Solar eclipse' plum production in semi-arid regions and provided valuable insights for those seeking to optimise *WUE* while maintaining both economic viability and agronomic performance.

Keywords: Japanese plum, optimising irrigation, physiological adaptation, sustainable production, water use efficiency (*WUE*)

INTRODUCTION

Water scarcity is a growing global concern, especially in arid and semi-arid regions where agriculture relies heavily on irrigation. The crisis, driven by climate change and population growth, highlights the urgency of water conservation in agriculture (FAO, 2021a; UN, 2025). Egypt, located in a semi-arid to arid zone, faces severe water shortages, making water-efficient irrigation essential for sustainable farming.

Plum (*Prunus salicina* L.) cultivation is important in Egypt for its nutritional and economical values. Although plums are sensitive to water fluctuations, recent research suggests that regulated deficit irrigation (DI), a technique that strategically limits water during less sensitive growth stages, can improve fruit quality while conserving water (Galindo *et al*., 2018; Hassan *et al*., 2021; Razouk *et al*., 2021). This aligns with global efforts toward climate-smart agriculture.

Utilising DI optimises water use efficiency (*WUE*) by activating plant stress responses that enhance drought resilience. While some yield loss may occur, studies show that DI maintains acceptable productivity and enhances fruit quality in peaches, nectarines, and plums (Girona *et al*., 2004; Egea *et al*., 2010). Water stress under DI also promotes beneficial metabolites, improving fruit sweetness and nutritional value (Mittler, 2002).

Key fruit quality traits such as total soluble solids (TSS), phenolics, and antioxidant capacity are improved under moderate water stress, increasing market value (Giusti and Wrolstad, 2001; Chaves, Maroco and Pereira, 2003; Blum, 2011). Despite these benefits, DI adoption remains limited, especially in countries like Egypt that use traditional irrigation.

This study evaluates DI's impact on yield, fruit quality, and *WUE* of 'Solar eclipse' plum, a cultivar released by Culdevco and known for its flavour and climate adaptability (Culdevco, 2025). Conducted over two seasons in an established orchard at El Tahadi Road, Nubaryia, the research compares DI to conventional irrigation (CI) and offers recommendations for water-efficient plum farming.

To understand how plum trees respond to water stress, the study examined anatomical, physiological, and biochemical traits, including proline, abscisic acid (ABA), and anthocyanins, which are key indicators of drought tolerance (Bates, Waldren and Teare, 1973; Giusti and Wrolstad, 2001; Sandhu *et al*., 2011; Hernandez-Santana, Rodriguez-Dominguez and Diaz-Espejo, 2016).

Relative water content (*RWC*) and leaf water deficit (*LWD*) are used to assess plant water status. The *RWC* reflects a leaf's hydration and structural stability (Barrs and Weatherley, 1962), while *LWD* quantifies the extent of water loss, inversely affecting *RWC* (Jones, 2007). These metrics help evaluate how irrigation strategies influence water relations in plum trees.

By exploring trade-offs between yield, *WUE*, and fruit quality, this study supports the adoption of DI for sustainable orchard management in arid regions. The findings contribute to global efforts in efficient water use and climate-resilient agriculture (FAO, 2021b). The aim of this study was to determine a deficit irrigation strategy for 'Solar eclipse' plum that maximises fruit quality while minimising water use in semi-arid climates.

MATERIALS AND METHODS

The experimental study was conducted in an established orchard at El Tahadi Road, Nubaryia, Egypt (30°43'54" N, 30°33'1" E), a reclaimed desert area with predominantly sandy soils and an arid region with less than 40 mm annual rainfall and average temperatures ranging from 10 to 35°C (EMA, 2025). The soil properties at 0–30 cm depth consisted of an 88% sand, 7% silt, 5% clay soil texture with a pH of 8.7, 3.4% calcium carbonate ($CaCO_3$) and 211 ppm total dissolved salts (*TDS*) (Tab. 1). Groundwater, pumped from a deep well at an approximate depth of 150–200 m, which reflects the actual groundwater table in the El Nubaryia region, was used to irrigate high-value 'Solar eclipse' plum trees to assess irrigation management under water scarcity.

Table 1. Soil and water analysis for the plum tree orchard in the El Tahadi Road, Nubaryia region of Egypt

Parameter	Value in soil (0–30 cm)	Value in water
pH	8.65	7.88
Sand (%)	88.0	–
Silt (%)	7.0	–
Clay (%)	5.0	–
Total dissolved salts (ppm)	211.2	250
$CaCO_3$ (%)	3.4	–
Ca^{2+} (meq·(100 g)$^{-1}$)	1.0	1.0
Mg^{2+} (meq·(100 g)$^{-1}$)	0.6	0.8
Na^+ (meq·(100 g)$^{-1}$)	1.4	1.49
K^+ (meq·(100 g)$^{-1}$)	0.1	0.45
Cl^- (meq·(100 g)$^{-1}$)	1.8	0.0
SO_4^{2-} (meq·(100 g)$^{-1}$)	0.4	0.8
CO_3^{2-} (meq·(100 g)$^{-1}$)	0	–
HCO_3^- (meq·(100 g)$^{-1}$)	0.9	1.0

Source: own elaboration.

The experiment was conducted for two years (2023–2024) using five-year-old trees spaced at 4 × 5 m, with the commercial cross pollinator "Pioneer" replacing one in every eight 'Solar eclipse' trees. Standard horticultural practices were followed. Irrigation treatments were applied at 100% crop evapotranspiration (ET_c) as the conventional irrigation (CI) or 50% ET_c as regulated deficit irrigation (DI) during fruit development, using a randomised complete block design with three replicates of 10 trees for each. The ET_c was estimated using the FAO Penman–Monteith model (Smith, Allen and Pereira, 2000), and crop coefficient (K_c) values were applied for each phenological stage. Weekly adjustments were made based on weather and soil moisture (Davie and Zhang, 1991). Drip irrigation with pressure-compensating emitters and tensiometers at 15, 30 and 45 cm depths ensured precision (Chaves, Maroco and Pereira, 2003).

Baseline soil and water analyses were conducted (Blum, 2011), and meteorological data were collected via an on-site weather station (Tab. 1). Yield per tree was recorded and expressed per ha. Agronomic water use efficiency (*WUE*) was calculated as yield per m^3 of irrigation water and computed based on the total volume of irrigation water applied, which was determined using the FAO Penman–Monteith approach and local meteorological data (Smith, Allen and Pereira, 2000; Farooq *et al.*, 2009). The applied water volumes for each treatment were CI, 100% ET_c ~26,800 $m^3 \cdot ha^{-1}$ and DI, 50% ET_c during fruit development ~13,400 $m^3 \cdot ha^{-1}$. The formula used for *WUE* (in $kg \cdot m^{-3}$) was:

$$WUE = \frac{Y}{I} \tag{1}$$

where: Y = total fruit yield ($kg \cdot ha^{-1}$), I = irrigation water applied ($m^3 \cdot ha^{-1}$).

For quality assessment, 20 fruits per tree were analysed. Total soluble solids (TSS) were measured with a digital refractometer (ATAGO PAL-1, Tokyo, Japan), while phenolics were quantified using the Folin–Ciocalteu method with modifications (Singleton, Orthofer and Lamuela-Raventós, 1999) and expressed as mg of gallic acid equivalents (GAE) per g of sample (mg GAE·g fresh mass^{-1}). Antioxidant capacity was assessed via the DPPH (1, 1-diphenyl-2-picrylhydrazyl) method (Brand-Williams, Cuvelier and Berset, 1995) and expressed as µmol Trolox per g of fresh mass (µmol Trolox·g^{-1}). Leaf proline was measured following Bates, Waldren and Teare (1973), and abscisic acid (ABA) concentrations were determined using enzyme-linked immunosorbent assay (ELISA) after methanol extraction with antioxidants (Walker-Simmons, 1987).

Anthocyanin content was measured using the pH differential method (Giusti and Wrolstad, 2001), with absorbance readings at 520 and 700 nm, and results expressed as cyanidin-3-glucoside equivalents. Lipid peroxidation was assessed via malondialdehyde (MDA) content using the thiobarbituric acid method, with absorbance at 532 and 600 nm (Heath and Packer, 1968). Relative water content (*RWC*) was calculated as:

$$RWC\ (\%) = \frac{FM - DM}{TM - DM} \cdot 100 \tag{2}$$

Fresh mass (*FM*), turgid mass (*TM*), and dry mass (*DM*) were determined by weighing leaves immediately after sampling, after 24 h in distilled water at 4°C, and after oven-drying, respectively. Leaf water deficit (*LWD*), a complementary measure to *RWC*, was calculated as:

$$LWD\ (\%) = \frac{TM - FM}{TM - DM} \cdot 100 \tag{3}$$

Data were tested for normality (Shapiro–Wilk) and homogeneity of variance (Levene's test). As no seasonal differences were found, data from both years were pooled. Treatment effects were analysed using analysis of variance (ANOVA) (SPSS v25, IBM), with post hoc Tukey's honest significant difference (HSD) tests applied at a 5% significance level.

RESULTS AND DISCUSSION

YIELD AND WATER USE EFFICIENCY

Averaged over the 2023 and 2024 seasons, significant differences were observed between the conventional irrigation (CI) and deficit irrigation (DI) treatments (Fig. 1). The CI trees consistently produced the highest yields, while DI trees yielded 16% less, emphasising the importance of adequate water supply for optimal fruit production as found by Chaves, Maroco and Pereira (2003), Blum (2011), Razouk *et al.* (2021) and Hamdani *et al.* (2022). Full irrigation supports essential physiological processes such as photosynthesis and nutrient uptake, ensuring

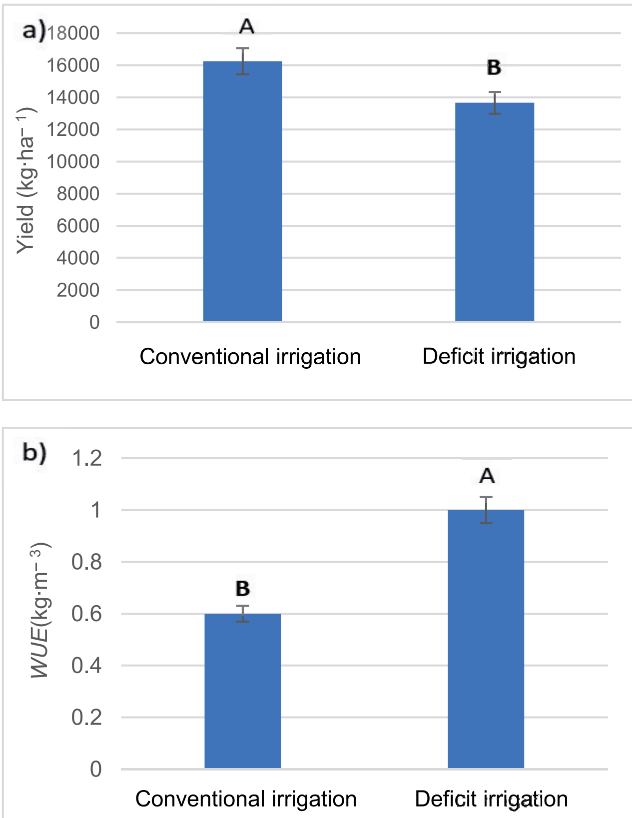


Fig. 1. Effect of irrigation regimes of 'Solar eclipse' plum on averaged over both seasons at El Tahadi Road, Nubaryia, Egypt: a) fruit yield, b) water use efficiency (*WUE*); capital letters indicate significant differences between means for each parameter ($P \leq 0.05$, Tukey's HSD); source: own study

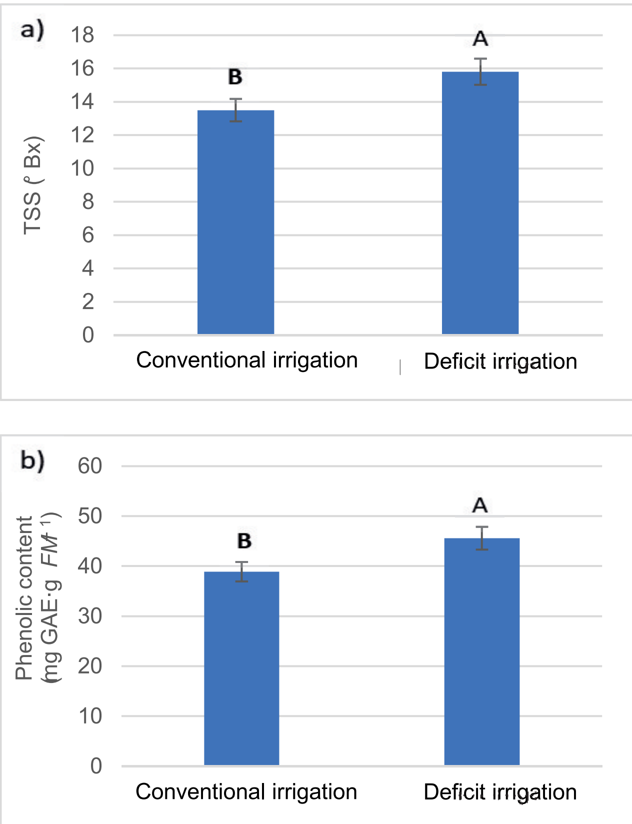
maximal yield (Zhang and Davies, 1990; Smith, Allen and Pereira, 2000; Temnani *et al*., 2023).

In contrast, DI significantly enhanced *WUE*, averaging 1.02 ±0.04 kg·m^{-3}, 67% higher than the CI trees, which emphasises its potential for sustainable water management in arid regions like El Tahadi Road, Nubaryia. This improvement is attributed to physiological adaptations, particularly ABA-mediated stomatal regulation that reduces transpiration and sustains carbon assimilation, which was concluded also by Zhang and Davies (1990). Similar *WUE* gains without major yield penalties have been reported in peaches, nectarines, and almonds (Girona *et al*., 2004; Egea *et al*., 2010; Razouk *et al*., 2021). Integrating DI with precision technologies could further enhance its efficiency and applicability in water-limited environments.

FRUIT QUALITY PARAMETERS

Trees under DI had several fruit quality parameters improved compared to CI trees (Fig. 2). Fruit from DI trees had 17% higher TSS, indicating enhanced sweetness. Fruit phenolic content and antioxidant capacity also increased significantly under DI, averaging 45.6 ±1.2 mg GAE·g^{-1} and 82.6 ±1.7 μmol Trolox·g^{-1}, respectively, compared to 38.9 ±0.9 mg GAE·g^{-1} and 74.3 ±1.5 μmol Trolox·g^{-1} under CI (P < 0.05).

These improvements reflect physiological and biochemical responses to water stress, such as sugar concentration during fruit ripening and activation of secondary metabolism as seen in the results from Girona *et al.* (2004) and Hassan *et al.* (2025). Elevated fruit phenolics and antioxidant capacity under DI are linked to enhanced reactive oxygen species (ROS) scavenging activity, driven by increased synthesis of phenolics and anthocyanins (Giusti and Wrolstad, 2001; Mittler, 2002; Jin *et al*., 2022).



In addition to their health benefits, anthocyanins improved the fruit pigmentation and visual appeal, which are key traits for consumer acceptance and market value. These findings support DI as a viable strategy to boost both the nutritional quality and market competitiveness of fruit in arid environments (Nasrabadi, Ramezanian and Valero, 2024).

BIOCHEMICAL MARKERS

Trees under water stress from DI during fruit development showed consistently elevated biochemical markers compared to trees under CI across both seasons (Fig. 3). Leaf proline and ABA levels increased by 80 and 72%, respectively, under DI, while anthocyanin content rose by 29%. Leaf MDA, an oxidative stress indicator, was 24% higher under DI, reflecting moderate stress.

The increase in proline under DI highlights its role in osmotic adjustment, helping maintain cell turgor and protect cellular structures under drought as reported by Bates, Waldren and Teare (1973). Elevated ABA levels reflect enhanced drought signalling, promoting stomatal closure and water conservation (Davies and Zhang, 1991). The moderate rise in MDA indicates that oxidative stress was present but effectively managed by antioxidant defences, including higher phenolic and anthocyanin synthesis (Mittler, 2002). These adaptive responses support DI as a resource-efficient alternative to CI, particularly in water-limited regions, consistent with prior findings in stone fruits (Ruiz-Sánchez, Domingo and Torrecillas, 2010; Alcobendas, Mirás-Avalos and Nicolás, 2013).

PHYSIOLOGICAL MARKERS

Water stress from DI during fruit development significantly affected physiological markers, with 16% higher *RWC* for trees under CI than DI (Fig. 4). This reflects better hydration and optimal physiological function under CI, due to consistent water availability as reported by José *et al.* (2013) and Hajlaoui *et al.* (2022). Conversely, lower *RWC* under DI indicates reduced water uptake and increased transpiration, though moderate levels suggest osmotic adjustment via compatible solutes like proline (Bates, Waldren and Teare, 1973; Egea *et al*., 2010).

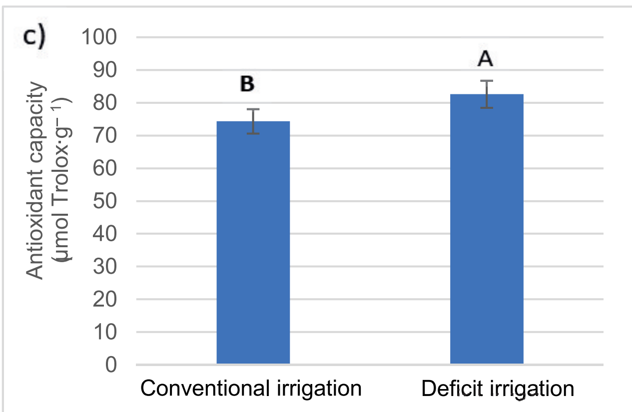


Fig. 2. Impact of irrigation regimes on fruit quality parameters of 'Solar Eclipse' plum, averaged over both seasons at El Tahadi Road, Nubaryia, Egypt: a) total soluble solids (TSS), b) phenolic content, c) antioxidant capacity; capital letters indicate significant differences between means for each parameter (P ≤ 0.05, Tukey's HSD); source: own study

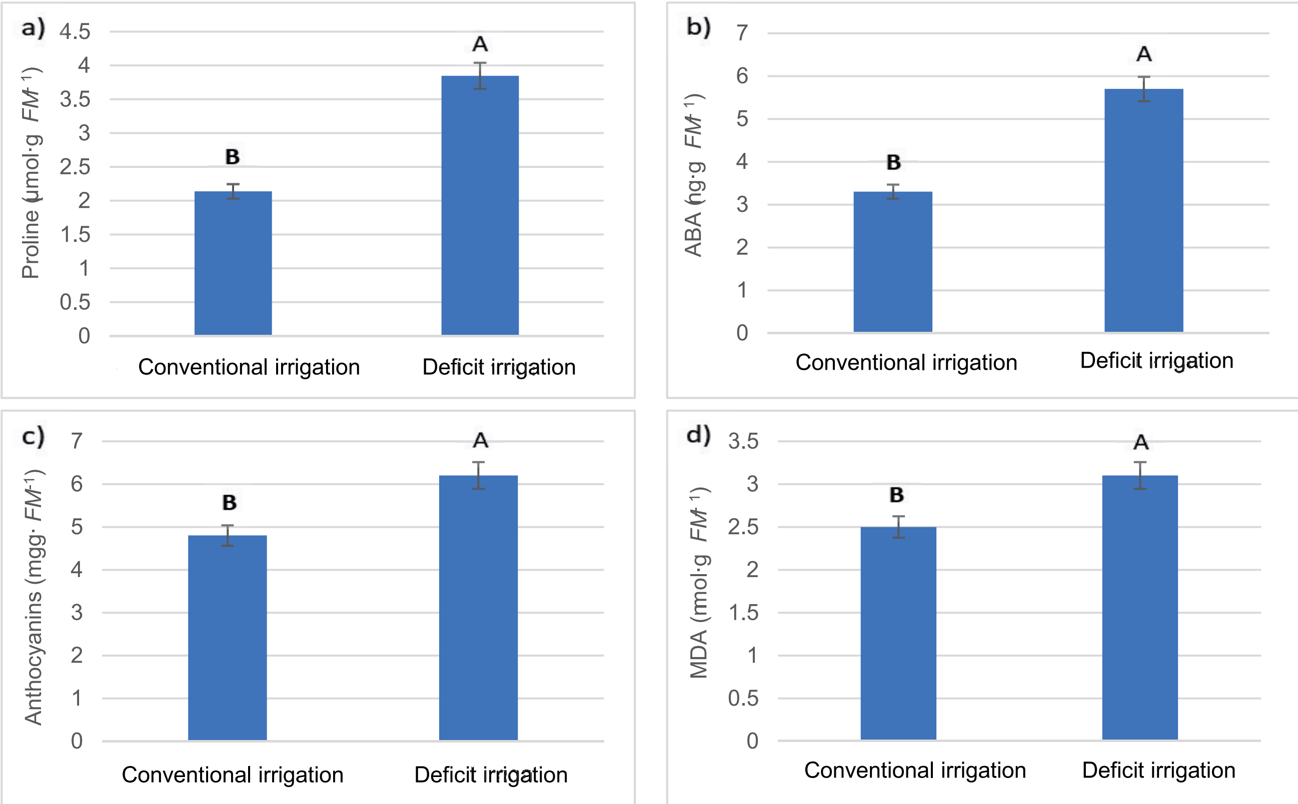


Fig. 3. Impact of irrigation regimes for 'Solar eclipse' plum averaged over both seasons at El Tahadi Road, Nubaryia, Egypt, on tree physiological and biochemical responses of: a) proline, b) abscisic acid (ABA), c) anthocyanins, d) malondialdehyde (MDA); capital letters indicate significant differences between means for each parameter ($P \leq 0.05$, Tukey's HSD); source: own study

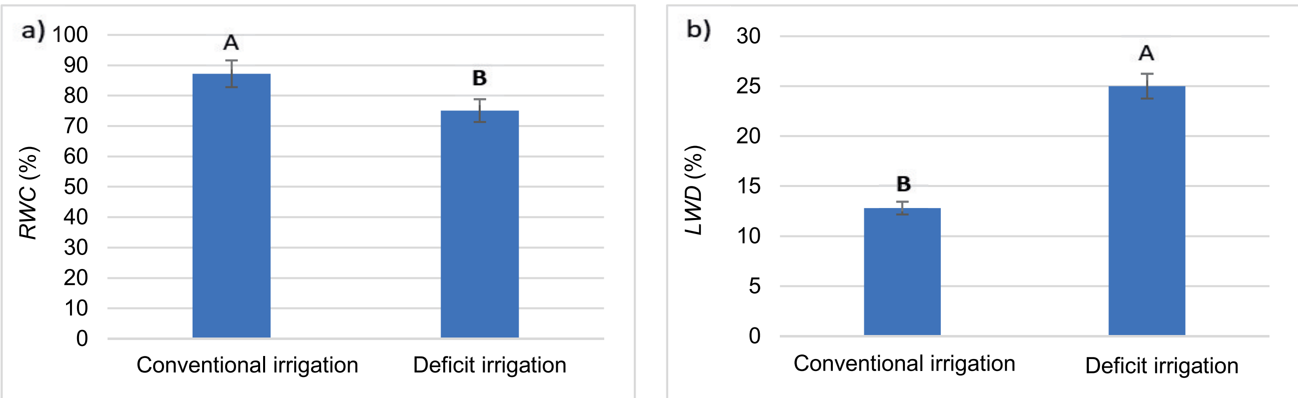


Fig. 4. Impact of irrigation regimes of 'Solar eclipse' plum averaged over both seasons at El Tahadi Road, Nubaryia on: a) relative water content (*RWC*), b) leaf water deficit; capital letters indicate significant differences between means for each parameter ($P \leq 0.05$, Tukey's HSD); source: own study

The *LWD* was nearly doubled for trees under DI (25.0%) compared to CI (12.8%), highlighting the plant's reduced ability to retain water and increased stress (Blum, 2011). The elevated *LWD* suggests lower turgor pressure and limited leaf expansion, which would impair photosynthesis and growth.

Despite the increased stress, DI remains economically and environmentally advantageous in water-limited regions, offering reduced input costs and enhanced fruit quality for high-value markets. Integrating DI with advanced monitoring technologies, such as remote sensing and real-time soil moisture tracking, should optimise its application and scalability as reported by Blum (2011), Hassan *et al.* (2022), and Elmenofy *et al.* (2023).

PARAMETER CORRELATIONS CHART

Biochemical stress markers, particularly proline, ABA, and anthocyanins, were highly interrelated ($r > 0.90$), indicating a coordinated response to water deficit (Fig. 5). Deluc *et al.* (2009) also showed that in 'Cabernet sauvignon' grapes, a water deficit significantly elevated ABA, proline, sugar, and anthocyanin concentrations and that the correlations among these biochemical markers were highly significant. The MDA content displayed moderate positive correlations with *WUE* ($r = 0.58$) and TSS ($r = 0.61$), which suggested that oxidative stress occurred, but was effectively managed by elevated antioxidant activity (Sandhu

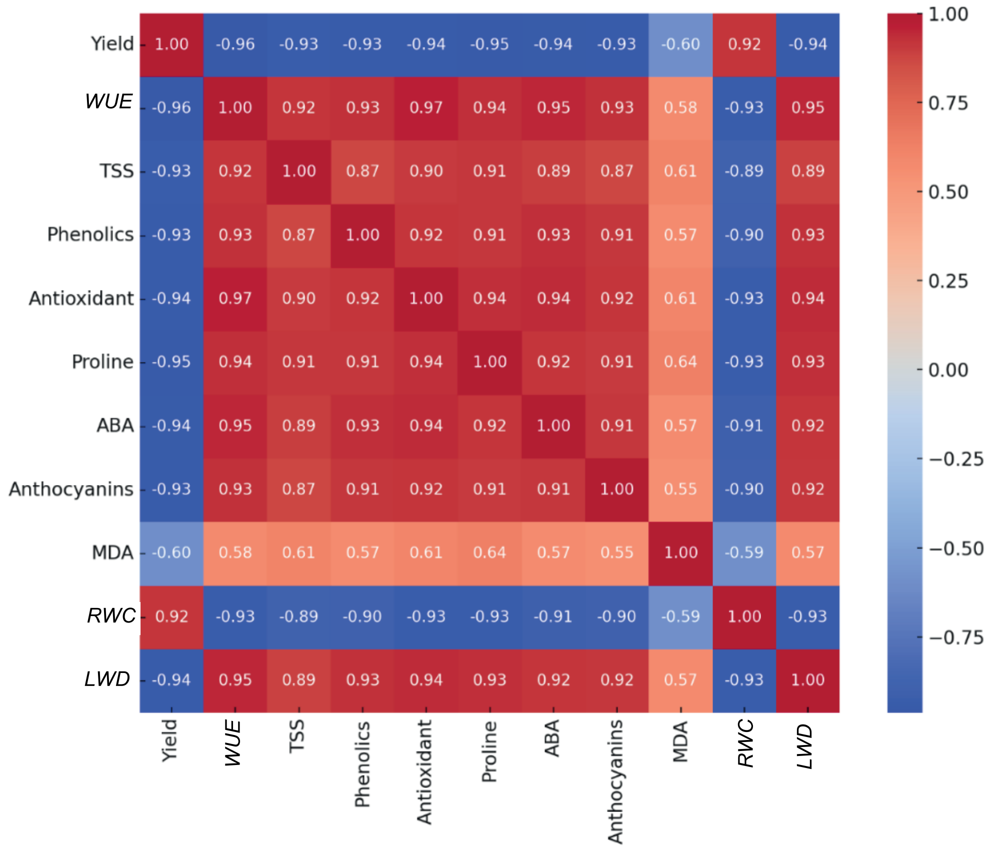


Fig. 5. Correlation heatmap demonstrating relationships among yield, water use efficiency (*WUE*), fruit quality traits (total soluble solids (TSS), phenolics, antioxidant capacity), biochemical parameters (proline, abscisic acid (ABA), anthocyanins, and malondialdehyde (MDA)) and physiological parameters (relative water content (*RWC*) and leaf water deficit (*LWD*)) of 'Solar eclipse' plum under control irrigation (CI) and regulated deficit irrigation (DI); positive correlations are indicated in red, negative correlations in blue, with colour intensity proportional to the correlation coefficient (*r*); source: own study

et al., 2011; Mihaljević *et al.*, 2021). The correlation chart also showed that *RWC* correlated strongly and positively with yield but negatively with *WUE* (r = –0.93), which highlighted the trade-off between maintaining hydration and improving water-use efficiency. In contrast, *LWD* exhibited strong positive associations with *WUE* (r = 0.95) and ABA (r = 0.94), reinforcing its role as a reliable stress indicator (Wijewardana *et al.*, 2019). Enhanced *WUE* and fruit quality under DI were closely linked to biochemical and hormonal signalling, reinforcing the need for regulated deficit irrigation as a climate-smart strategy when optimising water use without compromising economic returns. Enhanced *WUE* and fruit quality under DI were closely linked to biochemical and hormonal signalling, reinforcing the need for regulated deficit irrigation as a climate-smart strategy when optimising water use without compromising economic returns.

CONCLUSIONS

This study demonstrated the complex effects of irrigation regimes on the agronomic, physiological, and biochemical parameters of five-year-old 'Solar eclipse' plum trees under semi-arid conditions. While trees under CI maximised yield and were 16% higher compared to the yield from trees under DI, the trees under CI had a significantly lower *WUE* of 40% when compared to trees under DI. Trees receiving the DI had increased fruit quality parameters of TSS, phenolics and antioxidant capacity by 17%, 17% and 11%, respectively. Trees that received DI also had higher stress-related physiological responses compared to control trees with 80% greater proline concentration, 72% greater ABA concentration and 29% greater anthocyanin content. The *RWC* was 16% higher for trees under CI compared to DI, while the *LWD* was nearly doubled for trees under DI (25.0%) compared to CI (12.8%). The correlation analysis shows the complex interplay between physiological, biochemical, and yield-related parameters under contrasting irrigation regimes. A strong negative correlation between yield and key biochemical stress indicators, including ABA, proline, anthocyanins, and antioxidant capacity, emphasises the physiological cost of enhanced stress adaptation under DI. While DI reduced overall yield, it significantly improved *WUE*, fruit quality attributes (TSS, phenolics, antioxidants), and stress-responsive metabolites, suggesting a shift in plant resource allocation towards survival and quality rather than biomass production.

Conversely, yield was positively associated with *RWC*, reinforcing the importance of tissue hydration under full irrigation for maximising productivity. Strong positive correlations among *WUE* and ABA, proline, and secondary metabolites confirm the biochemical and hormonal adjustments associated with improved water productivity under DI. The observed interrelationships among biochemical markers further emphasise a tightly coordinated stress response network.

Collectively, these findings suggest that DI promotes physiological and biochemical mechanisms that enhance water efficiency and fruit quality at the expense of yield. Such trade-offs should be strategically considered in crop management, especially under increasing water scarcity, to optimise both resource use and crop value in water-limited environments. These findings also support DI as a sustainable strategy for balancing yield, quality, and resource use. Integrating DI with precision agriculture could further enhance its effectiveness, promoting climate-resilient plum production in semi-arid regions.

ABBREVIATIONS

ABA = abscisic acid
CI = traditional control irrigation
DI = regulated deficit irrigation
DM = dry mass
ELISA = enzyme-linked immunosorbent assay
ET_c = crop's evapotranspiration
ET_o = reference evapotranspiration (mm)
FM = fresh mass
GAE = gallic acid equivalents
K_c = crop coefficient
LWD = leaf water deficit
MDA = malondialdehyde
ROS = reactive oxygen species
RWC = relative water content
TSS = total soluble solids
TM = total mass
WUE = water use efficiency

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CONFLICT OF INTERESTS

All authors declare that they have no conflict of interest.

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