

Influence of Different Irrigation Levels on Anatomical Structure of Buds, Fertility, Productivity, and Fruit Quality of Flame Seedless Grapevines under Arid Climate Conditions

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ABSTRACT

Abiotic stresses, including drought, significantly impact growth and yield of grapevine. A field experiment was carried out in sandy loam soil in the Nubaria region of Egypt over three consecutive growing seasons. This study examined the effects of irrigation levels on water use efficiency (WUE), yield, fruit quality, and the anatomical structure of buds in 8-year-old Flame Seedless grapevines. Four irrigation regimes were implemented from pre-flowering to harvest: 125%, 100%, 75%, and 60% of field capacity (FC). Results demonstrated that the proportion of dried leaflets in buds and dried leaflet length increased with greater water stress in both seasons. The 60% FC deficit irrigation treatment reduced growth parameters, shoot length, leaf number, leaf area, cluster number, berries number, compactness coefficient, weight, and size of 100 berries, juice volume, and bud fertility percentage, leading to decreased yield in both seasons. In addition, cluster weight was significantly reduced by water deficit only in the second season. Cluster length was not significantly affected by water deficit, while cluster width decreased significantly under the 60% field capacity (FC) regime. There were no significant differences between 125% and 100% FC regarding the weight of 100 berries and juice volume. Irrigation at 125% FC and 100% FC resulted in greater berry diameter and length compared to 75% FC and 60% FC in both seasons. Irrigation levels did not substantially affect total soluble solids (TSS), acidity, or the TSS/acidity ratio, except for acidity and the TSS in the second season. The 75% FC treatments increased anthocyanin content relative to 125% FC and 100% FC in both seasons. Application of a 75% FC irrigation level is recommended for Flame Seedless grapevines to conserve water without reducing yield or fruit quality.

Keywords: deficit irrigation; Flame Seedless grapevines; buds; TSS/acidity ratio; cluster; berry; anthocyanin.

INTRODUCTION

Grapevine (*Vitis vinifera* L.) is among the most extensively cultivated fruits in Egypt and globally. Egypt produces about 1.4 million tons of grapes, with exports projected to reach 118,000 tons by 2022 (Ahmed *et al.*, 2023). Grapevines are particularly vulnerable to extreme drought conditions and a lack of water (Chaves *et al.*, 2010). When water is scarce (when the plant receives less water than needed), photosynthetic activity decreases, and carbohydrate levels (sugars produced by the plant for energy) may drop, leaving insufficient energy for the differentiation of inflorescences (the formation of flower clusters) (Lakatos and Mitre, 2023). Conversely, moderate water stress (less than optimal water but not severe deficiency) can improve bud fruitfulness because of lower canopy mass and greater bud light exposure, especially in the renewal area (where new shoots grow) (Tomás *et al.*, 2012). The process of inflorescence differentiation is particularly responsive to the synergistic impacts of nitrogen deficiency (which refers to a lack of nitrogen, a crucial nutrient for plants) and water scarcity (Guilpart *et al.*, 2014). Global warming is expected to increase water stress risk in most cultivated regions in the coming decades (Cramer *et al.*, 2018). Exposure to the synergistic impacts of drought (prolonged durations with minimal or absent rainfall), increased air temperature, and heightened evaporative demand in summer (greater water loss from soil and vegetation) can cause substantial harm to vines, leading to a marked decrease in grape yield and berry quality (Palliotti *et al.*, 2014 and Van Leeuwen & Destrac-Irvine, 2017). A large variability in WUE (Water Use Efficiency, meaning how much crop is produced per unit of water) among grapevine cultivars has been shown. Thus, selecting cultivars (choosing grape varieties) for high WUE appears promising for managing increasing challenges in viticultural farms (Tomás *et al.*, 2012).

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A lack of water has a considerable impact on the development of berries, leading to smaller berry sizes and higher levels of soluble sugars, total phenols, and anthocyanins. These physiological changes are partially attributed to the regulation of genes associated with grape quality under water-limited conditions. This relationship demonstrates a trade-off between yield and quality. Moderate water deficits are frequently applied in viticulture to enhance specific quality attributes (Alatzas *et al.*, 2021). The effects of water deficit on vine physiology and yield components vary depending on factors such as genotype, intensity and duration of water stress, soil moisture levels, and drought conditions (Geerts and Raes, 2009). A significant risk for viticulture is the potential increase in grape sugar concentration due to elevated temperatures. Deficit irrigation has been proposed as a strategy to mitigate this issue (Lakatos and Mitre, 2023). Maintaining appropriate water levels can enhance nitrate use efficiency, reduce nutrient and biocide leaching, and potentially affect water costs (Costa *et al.*, 2007). Different grapevine cultivars exhibit varying responses to water stress. Some cultivars display near-isohydric behavior, maintaining stable water status, while others exhibit near-anisohydric behavior, characterized by higher water use efficiency. These physiological responses may also vary within the same cultivar under different environmental conditions (Cogato *et al.*, 2022).

Vegetative growth and yield of grapevines decline as water deficit intensifies. Drought stress also diminishes fruit quality (Conde *et al.*, 2007 and El-Sayed *et al.*, 2024). Intense water stress, characterized by 20 percent of crop evapotranspiration (ETc), enhances the levels of soluble solids and anthocyanin content while diminishing the size of grapes (Calderan *et al.*, 2021). Early water stress alters the anatomical structure of cellular components and reduces cell wall flexibility by limiting the subsequent expansion of pericarp cells (Ojeda *et al.*, 2001). When grapevines are subjected to drought stress either before veraison or later in the season, anthocyanin content increases (Deluc *et al.*, 2009). Berry composition, including titratable acidity, soluble solids, anthocyanins, and polyphenols, is closely associated with vine water status. However, the relationship depends on the phenological stage, and the specific variable measured (Basile *et al.*, 2011).

A 31% reduction in irrigation relative to the control does not significantly affect yield, berries volume, total soluble solids (TSS), or total phenolic concentration (Weiler *et al.*, 2018). Moderate water stress alters berry composition by increasing sugar content, color, and flavor compounds (Castellarin *et al.*, 2007). Water stress applied during ripening more effectively enhances anthocyanin content than tannin content in Merlot

grapevines (Bucchetti *et al.*, 2011). Recent studies have analyzed the impact of post-veraison water deficit on the quality and yield of table grapes, employing machine learning algorithms to forecast berry quality at the time of harvest (Temnani *et al.*, 2022). Building on these findings, this research aims to study the effects of irrigation deficit on bud anatomy, growth, yield, and fruit quality of Flame Seedless grapes, and to identify optimal water management strategies that sustain yield.

MATERIALS AND METHODS

1. Field Experiment:

The experiment was done over three consecutive growing seasons (2022–2024) at a private farm in El-Nubaria city, El-Beheira Governorate, Egypt (30°39'32.6"N 30°03'18.1"E). Eight-year-old, uniform Flame Seedless grapevines were cultivated in sandy loam soil using a wire trellis system and drip irrigation, with a planting distance of 2 × 3 meters. Standard cultural practices for the farm were applied to all vines. Experimental treatments commenced in 2022 and included four irrigation regimes, applied from just one week pre-flowering to harvest: 125% (farm standard), 100%, 75%, and 60% of field capacity. In 2023, the average minimum and maximum temperatures were 21.6 °C and 27.8°C, respectively; in 2024, these values were 21.9 °C and 28.5 °C. The average annual rain was 168 mm in 2023 and 169 mm in 2024. Average relative humidity was 63% in 2023 and 64% in 2024 (El-Nubaria Meteorological Research Station, Agriculture Research Center).

2. Determination of Applied Irrigation Water (AIW):

It was measured according to Vermeiren and Jopling (1984):

$$AIW = \frac{ET_o \cdot K_c \cdot K_r \cdot I}{E_a}$$

where ET_o is a reference evapotranspiration (mm day⁻¹) measured according to Allen (1996),

K_c is the crop factor, K_r is the reduction factor, I is the irrigation intervals (day), and E_a is the efficiency of irrigation (90%).

Irrigation period was estimated according to Phocaides (2007):

$$t = \frac{(AIW \times A)}{q}$$

where t is the irrigation time (h), A is the area (feddan), and q is the dripper discharge (L h⁻¹). The soil moisture content was monitored by PMS710 Plant Soil Moisture Meter.

3. Determination Irrigation Water Use Efficiency (IWUE):

Irrigation water use efficiency (IWUE) was determined according to Payero *et al.* (2009) as follows:

$$IWUE = \frac{\text{Crop yield } \left(\frac{Kg}{Fed}\right)}{\text{Applied irrigation water } \left(\frac{m3}{Fed}\right)}$$

4. Soil analysis:

The physical and chemical characteristics of soil are shown in Table 1. Soil analysis was achieved according to Olsen and Sommers (1982).

5. The bud anatomical structure of Flame seedless grapevines:

Bud samples from grapevines were collected at harvest. The first and second buds on each shoot were selected randomly. The buds were immersed in a solution comprising 50% ethyl alcohol, glacial acetic acid, and 40% formaldehyde, mixed in a volume ratio of 90:5:5 (FAA). The tissue underwent dehydration with *n*-butanol and was subsequently embedded in paraffin wax (Sass, 1958). Cross sections, each measuring 12 micrometers in thickness, were created using a rotary microtome and subsequently stained with safranin and fast green (Johansen, 1940). The sections were examined under a light microscope at 40x magnification. The proportion of dried leaflets within each bud was determined by taking the number of dry leaflets, dividing it by the total count of leaflets, and then multiplying the result by 100. The average length of dried leaflets was determined by measuring the dry length of each leaflet and calculating the mean value.

6. Physiological and chemical properties of Flame seedless grapevines:

The growth characteristics at the moment of growth cessation, such as shoot length and leaf area, were assessed. Leaf area was measured utilizing a planimeter.

The average number of leaves was determined by counting four selected shoots from each vine. The percentage of bud fertility was computed by dividing the average number of clusters per vine by the total number of buds present on each vine, following Bessis (1960). On July 6, 2023, and June 30, 2024, the vines were harvested at TSS 16-17% (Badr & Ramming, 1994), and the total yield per vine was recorded. Five representative clusters per vine were selected for quality assessment. To evaluate berry quality parameters at harvest, an average of 100 representative berries per replicate was analyzed for each treatment (El-Ansary, 2017).

Physical properties of Flame grapevines were determined. Cluster weight and the weight of 100 berries were determined by digital balance, cluster length and width were measured by ruler, and the number of clusters was counted per vine and berries number was calculated per cluster. The compactness coefficient was calculated as the number of berries divided by cluster length. Berry length and diameter were measured with a vernier caliper. The size of 100 berries was determined by water displacement in a measuring cylinder; juice volume was measured using the same tool. Berry length (L) and diameter (D) were measured with a vernier caliper. The L/D ratio was calculated by dividing the berry length by the berry diameter.

Chemical properties: Total soluble solids (TSS) were measured using a refractometer (model ATC-1, Atago Co., Tokyo, Japan). Titratable acidity (TA), expressed as tartaric acid, was calculated by titration in grape juice with 0.1 N NaOH to the endpoint using phenolphthalein indicator (AOAC, 1995). The TSS/acidity ratio was also calculated. Total anthocyanin was extracted with acidified ethanol and quantified by spectrophotometry at 535 nm and expressed as mg/100g of fruits (Hsia *et al.*, 1965).

Table 1. Some physical and chemical characteristics of the soil

Soil Physical characteristics	Value	Soil chemical characteristics	Value
Sand	81.0	pH 1:2.5	8.06
Silt	2.0	EC (dS/m)	0.85
Clay	17.0	Ca ²⁺ (meq/l)	2.0
Soil Texture	Sandy loam	Mg ²⁺ (meq/l)	1.8
Bulk density (kg/m ³)	1.45	Na ⁺ (meq/l)	4.6
Field capacity (%)	22.5	K ⁺ (meq/l)	0.5
Permanent Wilting point (%)	9.5	CO ₃ ²⁻ (meq/l)	0.0
		HCO ₃ ⁻ (meq/l)	3.0
		Cl ⁻ (meq/l)	4.1
		SO ₄ ²⁻ (meq/l)	1.8

7. Statistical analysis:

The experimental design was a randomized complete blocks design with three replications per treatment and five vines per replicate. Analysis of variance was achieved according to Gomez and Gomez (1984) and the Statistical Analysis System (SAS) software program version 9.1 (Castellari SAS Institute Inc, 2004) with the new LSD test at the 5% level of probability.

RESULTS

1. Anatomical structure of grapevine buds:

The leaflets within the bud remained fully hydrated, with no significant dryness observed under 125% and 100% of field capacity treatments. Excess water at

125% FC did not adversely affect the buds. Dryness was first detected in the outer leaflets under the 75% FC treatment, although this did not impact the inner leaflets. At 60% FC, increased dryness was observed in the outer leaflets, and dryness also appeared in the inner leaflets. Across both seasons, the proportion of dried leaflets increased as water stress intensified. During the first season, the 125% FC treatment recorded the lowest average dried leaflet length, with no significant differences among the other treatments. In the second season, the average dried leaflet length increased with a greater water deficit. No significant variations were found concerning the 125% FC and 100% FC, 100% FC and 75% FC, and 75% FC and 60% FC treatments, as shown in Table 2 and Figures 1, 2, 3, and 4.

Table 2. Effect of irrigation levels on buds' anatomy of Flame seedless grapevines in 2023 and 2024 seasons

Irrigation levels	Dried leaflet, %		Dried leaflet length, μm	
	2023	2024	2023	2024
125% FC	14.66 d	15.16 d	443.3 b	426.7 c
100% FC	18.56 c	18.60 c	1110.0 a	1370.0 bc
75% FC	37.16 b	36.66 b	1386.7 a	3610.0 ab
60% FC	52.00 a	53.00 a	1400 a	4880.0 a
New L.S.D.05	2.23	1.59	376.9	2250.1

* Different small letters range to show the significant differences between values separately for each parameter.

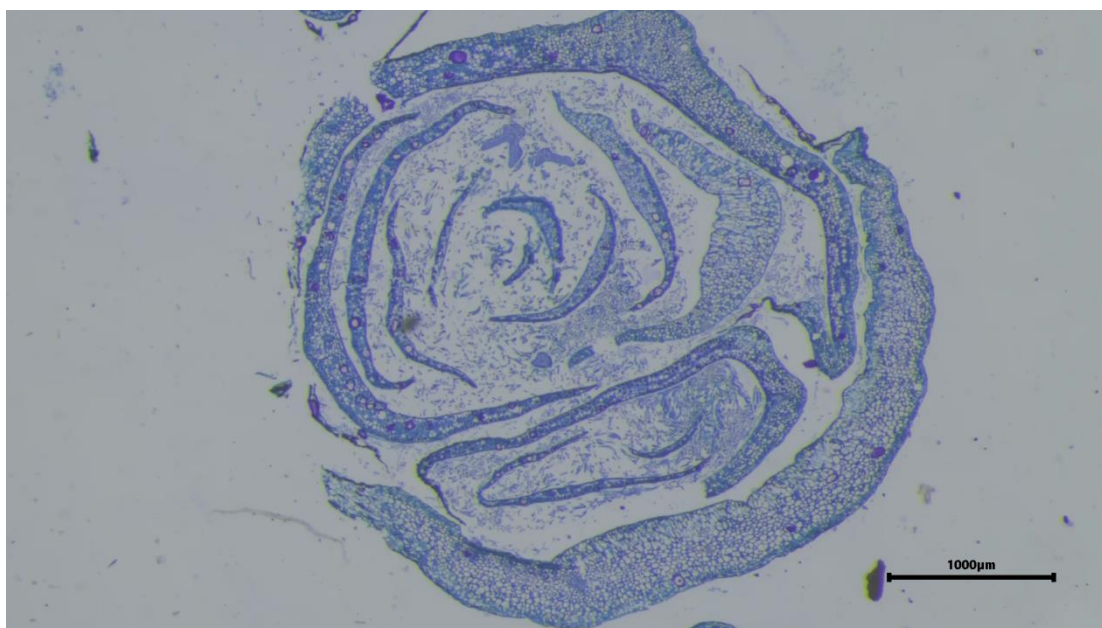


Figure 1. Anatomical structure of grapevine buds under 125% field capacity, notes that there is no dryness of leaflets edges.

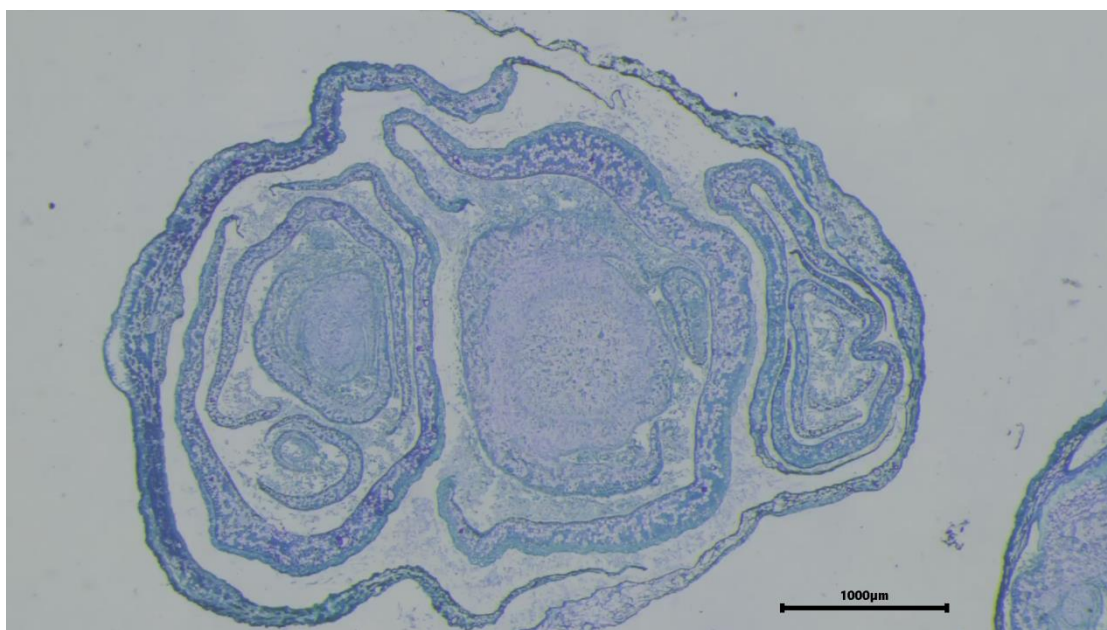


Figure 2. Anatomical structure of grapevine buds under 100% field capacity, notes the little dryness of sum leaflets edges.

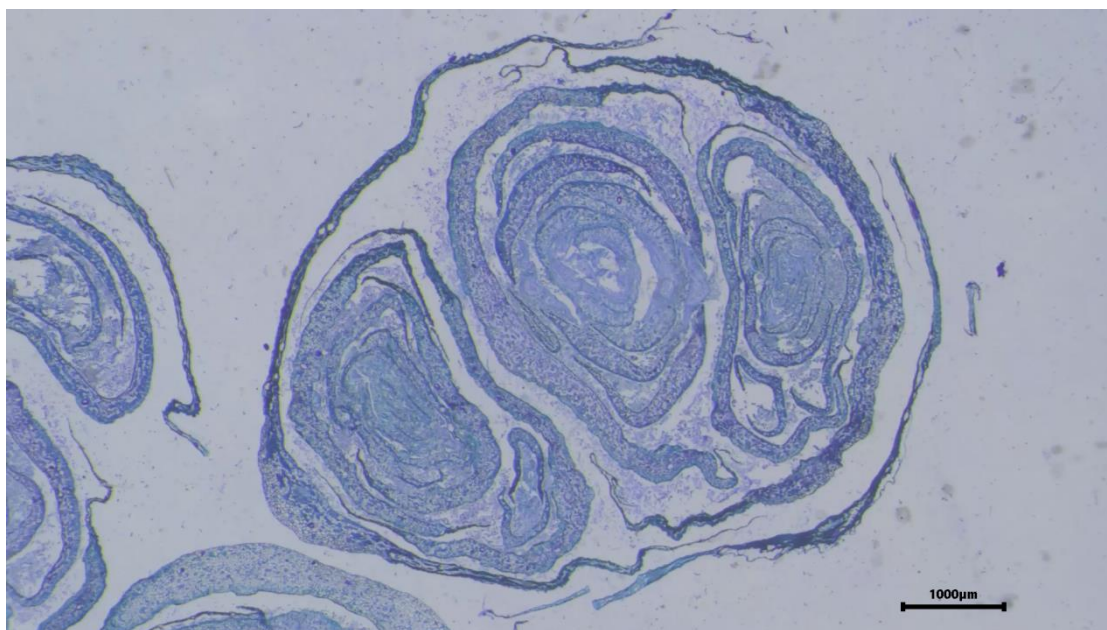


Figure 3. Anatomical structure of grapevine buds under 75% field capacity, notes the semi dryness of leaflets edges.

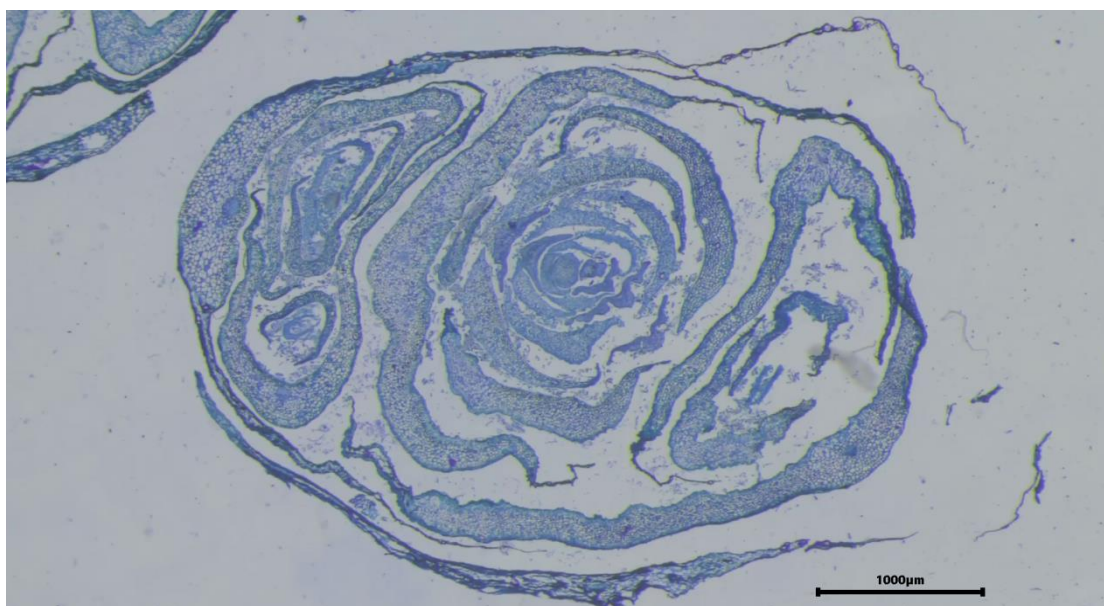


Figure 4. Anatomical structure of grapevine under 60% Field capacity, notes the high dryness of leaflets edges.

2. Vegetative growth properties of Flame seedless grapevine:

Regarding shoot length, 125% FC and 100% FC treatments recorded considerably greater shoot length than the 60% FC treatment in both seasons. Both seasons showed no significant variation in shoot length between the 100% FC and 75% FC treatments. Water deficit caused a significant reduction in leaf area; however, the treatments at 125% FC and 100% FC showed no substantial difference in both seasons. Leaves number was affected by water deficit in both seasons; 125% FC and 100% FC treatments had markedly greater leaves number than 60% treatment. Meanwhile, there were no remarkable differences between 75% and 60% applications in both seasons (Table 3).

3. Physical properties of Flame seedless grapevine:

According to the information in Table (4), there

was a marked reduction in cluster count and bud fertility percentage as water stress levels rose in both seasons, while the second season showed no noteworthy difference between 75% FC and 60% FC. Consequently, in both seasons the remarkably highest yield was recorded with 125% FC treatment and did not differ significantly from 100% FC and 75% FC applications. Meanwhile, the 60% FC treatment gave the considerably lowest yield (Table 4). The data showed that cluster weight was not considerably affected by the water deficit in the first season. However, there were highly remarkable differences among irrigation regimes in the second season. Besides, 125% FC treatment had the considerable cluster weight while 60% FC application gave remarkable lowest value. On the other hands, both the 100% FC and 75% FC treatments showed no notable differences (Table 4).

Table 3. Effect of irrigation levels on vegetative growth properties of Flame seedless grapevine in 2023 and 2024 seasons

Irrigation levels	Shoot length, cm		Leaf area, cm ²		Leaves number	
	2023	2024	2023	2024	2023	2024
125% FC	85.66 a*	83.66 a	155.00 a	153.33 a	14.00 a	13.33 a
100% FC	85.00 ab	83.33 a	154.66 a	153.00 a	14.33 a	13.66 a
75% FC	84.33 b	83.66 a	152.66 b	150.66 b	13.33 bc	12.66 b
60% FC	81.33 c	80.33 b	150.00 c	148.33 c	12.66 c	12.33 b
New L.S.D 0.05	0.94	1.85	1.45	1.37	0.74	0.66

* Different small letters range to show the significant differences between values separately for each parameter.

Table 4. Effect of irrigation levels on clusters number, cluster weight, bud fertility% and yield of Flame seedless grapevines in 2023 and 2024 seasons

Irrigation levels	Clusters number		Bud fertility%		Yield, kg/vine		Cluster weight, g	
	2023	2024	2023	2024	2023	2024	2023	2024
125% FC	64.00 a*	56.00 a	91.42 a	79.99 a	23.96 a	14.55 a	692.50	485.00 a
100% FC	62.00 a	62.66 b	88.56 a	89.52 b	23.45 a	14.41 a	645.00	415.00 b
75% FC	51.33 b	51.33 bc	73.32 b	73.33 bc	21.08 a	12.70 ab	680.00	400.83 b
60% FC	47.33 c	45.33 c	67.61 c	64.75 c	16.50 b	10.35 b	550.00	345.00 c
New L.S.D 0.05	3.52	6.49	5.03	9.27	2.95	2.39	114.49	53.03

* Different small letters range to show the significant differences between values separately for each parameter.

There were no significant differences in cluster length among irrigation applications in both seasons. Cluster width was not greatly affected by the 125% FC, 100% FC, and 75% FC levels, but these treatments resulted in significantly wider clusters than the 60% regime in both seasons. Regarding berries number (Table 5), 125% FC and 100% FC treatments gave considerably greater berries number, compared to the 60% FC application, and did not significantly differ from the 75% FC treatment in both seasons. Compactness coefficient values (Table 5) were significantly higher in 125% FC and 100% FC levels than in 60% treatment in both seasons; nonetheless, in the second season, there were no significant variations among the 125% FC, 100% FC, and 75% FC levels. Berry length did not show a significant response to different irrigation levels in the first season. In the second season, the 125% field capacity treatment produced the longest berries, and there was no notable

variation between the 125% and 100% field capacity treatments. 100% field capacity treatments. However, the 60% FC regime recorded remarkably the lowest berry length and did not markedly differ from 75% FC application. In both seasons, 125% FC and 100% FC irrigation levels had significantly greater berry diameter than the 60% FC treatment but did not significantly differ from 75% application. Length/diameter ratio (L/D) was not remarkably affected by water deficit applications in both seasons (Table 6).

In the first season, weight of 100 berries was not significantly affected by 125% FC, 100% FC and 75% FC applications. On the other hand, 60% treatment recorded the remarkably lowest weight of 100 berries. In the second season, 125% gave the considerably greatest weight of 100 berries while 60% had the significantly lowest value.

Table 5. Effect of irrigation levels on cluster length, cluster width, berries number and compactness coefficient of Flame seedless grapevines in 2023 and 2024 seasons

Irrigation levels	Cluster length, cm		Cluster width, cm		Berries number		Compactness coefficient	
	2023	2024	2023	2024	2023	2024	2023	2024
125% FC	19.33 a*	19.00 a	15.50 a	15.33 a	174.33 a	164.66 a	9.04 a	8.68 a
100% FC	20.50 a	18.00 a	15.50 a	15.33 a	169.33 a	167.66 a	8.26 ab	9.33 a
75% FC	20.00 a	18.00 a	15.00 a	14.33 a	156.66 a	146.66 b	7.86 bc	8.15 a
60% FC	19.66 a	17.66 a	13.66 b	12.66 b	140.66 b	115.00 c	7.13 c	6.52 b
New L.S.D 0.05	N.S	N.S	0.99	1.15	22.67	14.25	0.95	1.26

* Different small letters range to show the significant differences between values separately for each parameter.

Table 6. Effect of irrigation levels on berry length, berry diameter and L/D ratio of Flame seedless grapevine in 2023 and 2024 seasons

Irrigation levels	Berry length, mm		Berry diameter, mm		L/D ratio	
	2023	2024	2023	2024	2023	2024
125% FC	19.83 a*	19.50 a	18.50 a	18.50 a	1.070 a	1.050 a
100% FC	19.83 a	19.33 ab	18.50 a	18.16 a	1.070 a	1.060 a
75% FC	19.00 a	18.33 bc	17.66 ab	17.66 ab	1.073 a	1.036 a
60% FC	18.00 a	17.33 c	16.66 b	16.33 b	1.076 a	1.060 a
New L.S.D 0.05	N.S	1.03	1.20	1.40	N.S	N.S

* Different small letters range to show the significant differences between values separately for each parameter.

Table 7. Effect of irrigation levels on berries weight, berries size and juice volume of Flame seedless grapevines in 2023 and 2024 seasons.

Irrigation levels	Weight of 100 berries, g		Size 100 berries, ml		Juice volume, ml	
	2023	2024	2023	2024	2023	2024
125% FC	460.00 a*	417.50 a	413.33 a	373.33 a	391.66 a	371.67 a
100% FC	457.56 a	410.83 a	388.33 b	375.00 a	368.33 b	361.67 ab
75% FC	436.67 a	384.7 b	363.33 c	345.00 b	355.00 b	331.67 bc
60% FC	385.00 b	343.33 c	333.33 d	320.00 b	335.00 c	306.67 c
New L.S.D 0.05	38.71	24.70	11.16	26.58	21.94	30.10

* Different small letters range to show the significant differences between values separately for each parameter.

In the first season, the volume of 100 berries was remarkably reduced by increasing water stress. In the second season, the 125% FC and 100% FC watering levels had a considerably higher size of 100 berries than the 75% FC and 60% FC applications (Table 7). In both seasons, vines under 125% FC irrigation level had significantly the greatest juice volume with no difference from those vines irrigated with 100% FC level in the second season. The 60% FC treatment recorded the considerably lowest value (Table 7).

4. Chemical properties of Flame seedless grapevine:

In both seasons, the levels of irrigation did not show any notable variations in total soluble solids (Table 8). Acidity was not affected by water deficit in the first season, but it remarkably decreased as water stress

increased in the second season. In the first season, there were no significant variations in the TSS/acidity ratio across the various irrigation treatments. However, in the second season, a greater water deficit notably enhanced the TSS/acidity ratio. In both seasons, 75% FC irrigation level had the considerably highest anthocyanin content and did not markedly differ from 125% FC and 60% FC in the second season. Nevertheless, the 100% FC treatment resulted in the lowest concentrations across both seasons (Table 8).

5. Irrigation Water Use Efficiency (IWUE):

Figure 5 illustrates the impact of different irrigation levels on irrigation water use efficiency (IWUE) for the 2023 and 2024 seasons.

Table 8. Effect of irrigation levels on chemical properties of Flame seedless grapevines in 2023 and 2024 seasons

Irrigation levels	TSS %		Acidity %		TSS/acidity		Anthocyanin	
	2023	2024	2023	2024	2023	2024	2023	2024
125% FC	16.00 a*	16.00 a	0.66 a	0.67 a	24.00 a	23.76 c	24.93 b	29.73 a
100% FC	15.83 a	15.83 a	0.62 a	0.65 b	25.48 a	23.98 c	16.20 c	17.63 b
75% FC	16.00 a	16.16 a	0.64 a	0.64 c	25.00 a	25.14 b	47.20 a	37.83 a
60% FC	16.16 a	16.33 a	0.62 a	0.61 d	26.08 a	26.79 a	25.10 b	29.66 a
New L.S.D 0.05	N.S	N.S	N.S	0.005	N.S	1.02	7.21	8.24

* Different small letters range to show the significant differences between values separately for each parameter.

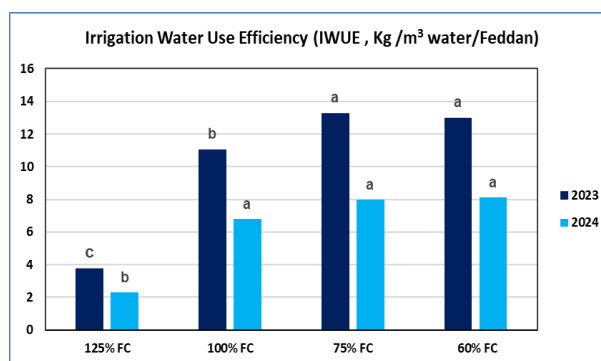


Figure 5. Irrigation water use efficiency in 2023 and 2024 seasons, columns with the same letter are not significantly different separately for each season

Throughout both seasons, it is evident that IWUE increased as the quantity of practical water declined. Notably, the 60% FC treatment gives the highest IWUE compared to the rest of the irrigation levels. While IWUE showed no significant difference between 75% FC and 60% FC treatments in the 2023 season, no remarkable changes among 100% FC, 75% FC, and 60% FC applications were observed in the 2024 season.

DISCUSSION

Drought stress results in a radical decrease of shoot expansion and sum leaf area advancement in aid of a higher biomass distribution and division towards roots, where most of the nonstructural carbohydrate reserves were also bottled. The dry material value of the enduring organs increased in stressed plants because of development reduction, distribution of carbon reserves, and probable anatomical alteration. Thus, a greater nonstructural carbohydrate in petioles, accepting the theory that they are occupied as suitable solutes in osmotic regulation (Vuerich *et al.*, 2021). The water case in grapevines influences the development and differentiation of inflorescence primordia through both direct and indirect effects on biochemical and biosynthetic processes, specifically in maintaining cell turgidity, enhancing photosynthetic activity, and facilitating the movement of nutrients and photoassimilates (Xylem, 2000; Vasconcelos *et al.*, 2009; Li-Mallet *et al.*, 2016 and Jackson, 2020).

A proper supply of water enhances the differentiation of inflorescences, resulting in greater bud fruitfulness. Conversely, when water is limited, both the number and size of inflorescences suffer (Magalhães, 2008). As plant water stress intensified, the quantity and weight of Cabernet Sauvignon inflorescences gradually diminished, resulting in a reduced yield for each plant (Buttrose, 1974 and Weiler *et al.*, 2018). The decrease in photosynthetic activity may lead to an inadequate supply of carbohydrates, which might not meet the energy needs for inflorescence differentiation (Magalhães, 2008). Conversely, mild water stress can enhance the fruitfulness of buds by decreasing canopy density and allowing better light exposure to the buds, particularly in the renewal zone (Keller *et al.*, 2005). Then, the anatomy of the current year's grape buds is a quick way to reflect the water status in the current year, growth, and grapevines yield for the next year. The differences in the grapevine's yield are mainly genetic factors, plant age, climatic conditions, fruitfulness, and fertilization (Lisek, 2014). Also, It was remarkably affected by increased water deficit (Faci *et al.*, 2014), whereas the TSS concentration improved when water stress was enhanced (Pérez *et al.*, 2017). Acidity decreased as the water deficit increased (dos

Santos *et al.*, 2007). The experiment on deficit irrigation took place in the early phase of berry growth (Phase I, referred to as the herbaceous phase), while different stressors were noted during the post-veraison stage (Phase II, or the ripening phase), which can greatly influence biochemical and molecular processes (Ollat *et al.*, 2002 and Berdeja *et al.*, 2015). The vine water case had a greater effect on the levels of skin tannin and anthocyanin than the size of the fruit had on those attributes (Roby *et al.*, 2004). It has been proven that early water deficits, occurring from flowering to ripening, cause a decrease in pericarp volume, which negatively impacts berry, weight and size (Ojeda *et al.*, 2001).

The diversity in anthocyanin structure shown in relation to the partial rootzone drying could not be considered due to alterations in bunch microclimate and was probably due to differences in the methylation step of anthocyanin composition (Bindon *et al.*, 2008). Water stress reduced the net CO₂ exchange rate and vine canopy area (Basile *et al.*, 2011). Grapevine leaves involve abundant CaOx crystals placed either within the mesophyll in the style of raphides or in the mass sheaths as druses. CaOx crystals function as inner carbon puddles supplying CO₂ for a beginning level of photosynthesis, called “alarm photosynthesis,” regardless of locked stomata; therefore, avoiding the photoinhibition and the oxidative hazard because of carbon malnutrition under deleterious conditions (Kolyva *et al.*, 2023). The decrease in IWUE was caused by a significant reduction in Amax, indicating that the leaves showed either high photorespiration rates or biochemical compromise (Pagay *et al.*, 2022). Water deficit during the stage from fruit set to veraison heavily decreases the berry size of Shiraz grapevines (McCarthy, 1997). In plants experiencing water stress, there was a notable decline in relative water content, leaf dry matter, chlorophyll levels, net photosynthetic rate (PN), as well as in RuBPC and NR activities. Alongside this, total leaf protein content diminished while the amount of free amino acids collected rose. At the same time, protease activity within the tissues increased. A remarkable two-fold rise in proline levels was recorded (Bertamini *et al.*, 2006).

Yield was decreased by deficit irrigation applications in the past season. This reduction in yield was mainly a result of lower clusters per vine, which in sequence was a blunt result of fewer shoots per vine. The smaller crop load on the grapevines that had been subjected to limited irrigation post-veraison in the past season led to greater sugar and anthocyanin levels in the next season. Post-veraison water stress has the possibility to affect both yield and fruit structure during

the current season, in addition to during the following season (Petrie *et al.*, 2004).

The use of an innovative decision support system (DSS) enabled a reduction of 10% to 17% in irrigation water, effectively sustaining good yield and quality in contrast to standard farm irrigation practices. Furthermore, the average weight of clusters showed no significant variation between the two irrigation techniques. However, during the 2020 season, the vines that received water from traditional farm systems produced considerably more berries and had longer clusters (Garofalo *et al.*, 2023). Significant water shortages greatly hindered the second growth stage of the berries, leading to varying degrees of size reduction among the fruits. However, the initial phases of sugar accumulation and color stability were not affected. In some well-watered varieties, véraison progressed normally or was even supported. Despite a notable drop in sugar content per fruit, the loss of strength in photoassimilates was substantial, even under extreme water scarcity, which resulted in partial leaf drop, inhibited fruit growth, and berry size reduction. These findings raise concerns about phloem mass flow and sugar concentration during severe water deficits. A moderate level of water stress proved beneficial for the ripening process in terms of individual berry development and sugar accumulation, but was less effective for varieties that matured well under adequate watering (Shi *et al.*, 2023).

Regarding the 'Crimson Seedless' grapevines, implementing deficit irrigation after véraison, with a water stress integral ranging from 22 to 30 MPa day and maintaining a stem water potential below -1.2 MPa, enabled the plant to reach its optimal productivity while preserving berry firmness and enhancing color. This method also achieved approximately 40% water savings compared to the control. Using Gaussian process regression effectively predicts berry color and firmness at harvest, taking into account the levels of water stress and fruit load, which helps inform cultural practices to mitigate potential color issues that could impact consumer preferences (Temnani *et al.*, 2022). Moderate water stress primarily impacts cell turgor; severe water deficiency also negatively influences other physiological functions like photosynthesis and solute transport (Kramer and Boyer, 1995). High levels of water stress diminish the ability to produce crops, hinder evaporation, reduce shoot length, lower yields, and affect fruit quality (Lovisolo *et al.*, 2008). An extreme shortage of water following véraison seriously limits sugar gathering. As a result, the ripening phase might fail, causing the berries to remain unripe with diminished sugar levels (Baeza *et al.*, 2019).

Significant water shortages, indicated by a dryness index under -100, lead to a notable decline in the sugar concentration of the berries. However, traditional agricultural methods cannot achieve peak sugar content. Due to the problem of overly high sugar content in many grape-growing areas, implementing deficit irrigation can provide a viable solution (Lakatos and Mitre, 2023). The water status of both rootstocks was affected by unsatisfactory irrigation systems before and after véraison. A notable impact on the trunk diameter (TD) increase was observed when water was restricted early, but this effect was absent in the period following véraison. Insufficient water from the time of fruit set until véraison hampered vegetative growth—reflected in TD, canopy size, and pruned wood weight—more significantly than the water deficiency from véraison up to harvest. Yield showed no variation related to either irrigation or rootstock across the two years. Nonetheless, irrigation played a crucial role in determining berry and juice quality: the water shortage before véraison (RDI 1) led to the highest levels of berry anthocyanins and the lowest titratable acidity (TA), while the TA rose during the post-veraison deficit (RDI 2). The RDI treatments did not impact the dry weight of berries, the content of soluble solids, TA, anthocyanins, or total phenols in the epicarp of vines from both rootstocks (Caruso *et al.*, 2023).

The goal of increasing water use efficiency is to conserve more water in dry climates, particularly in light of drought stress stemming from climate shifts and restricted water supply. The results indicated that there were no notable yield differences in the treatments of 125%, 100%, and 75% FC during both seasons. Therefore, it can be concluded that irrigating crimson grape at 75% FC is advisable for greater water conservation. Conversely, while the 60% FC treatment achieved the highest irrigation water use efficiency, it adversely affected grape yield due to the deficits in water supply. This corresponds with the findings of El-Sayed *et al.* (2024), which demonstrated that reducing irrigation to 60% FC diminished yield, whereas 75% FC offered the best balance for water conservation and production maintenance. Also, Weiler *et al.* (2018) reported that decreasing of irrigation amount by 31% did not have a significant negative effect on grape yield.

CONCLUSIONS

The current study focuses on conserving water used for irrigation during the period between pre-flowering and harvesting of Flame seedless grapevines under arid climatic conditions in sandy loam soil. Findings indicated that Buds maintained full hydration under 100–125% FC, whereas progressive water deficits (75–60% FC) induced increasing leaflet desiccation, initially in outer tissues and extending inward under severe

stress. Despite seasonal variation, treatment differences were largely non-significant, indicating bud resilience to moderate water deficits but heightened susceptibility under pronounced drought. Deficit irrigation significantly influenced Flame Seedless grapevine performance, with severe stress at 60% FC reducing vegetative growth, bud viability, yield components, and fruit quality traits. While 125% and 100% FC maintained optimal growth and berry development, 75% FC effectively enhanced water use efficiency without compromising yield or key quality parameters, apart from a moderate increase in anthocyanin accumulation. These findings suggest that regulated deficit irrigation at 75% FC is an optimal strategy for balancing water conservation and sustainable grapevine production under sandy loam soils in arid regions.

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الملخص العربي

تأثير مستويات الري المختلفة على التركيب التشريحي للبراعم، والخصوبة، والإنتاجية، وجودة ثمار عنب الفليم اللابذرى تحت ظروف المناخ الجاف

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الموسم الثاني. لم يتأثر طول العنقود تأثيراً معنوياً بنقص الري، بينما انخفض عرض العنقود معنوياً تحت نظام الري عند ٦٠٪ من السعة الحقلية. لم تلاحظ فروق معنوية بين الري عند ١٢٥٪ و ١٠٠٪ من السعة الحقلية من حيث وزن حبة وحجم العصير. أدى الري عند ١٢٥٪ و ١٠٠٪ من السعة الحقلية إلى زيادة قطر وطول الحبة مقارنة بالري عند ٧٥٪، و ٦٠٪ من السعة الحقلية في كلا الموسمين. لم تؤثر مستويات الري بشكل كبير على المواد الصلبة الذائبة الكلية أو الحموضة أو نسبة المواد الصلبة الذائبة إلى الحموضة، باستثناء الحموضة والمواد الصلبة الذائبة في الموسم الثاني. زاد محتوى الأنثوسيانين في معاملة ٧٥٪ من السعة الحقلية نسبة إلى معاملتي ١٢٥٪ و ١٠٠٪ في كلا الموسمين. يوصى بتطبيق مستوى ري يعادل ٧٥٪ من السعة الحقلية لكروم عنب فليم اللابذرى بهدف توفير المياه دون التأثير السلبي على المحصول أو جودة الثمار.

الكلمات المفتاحية: نقص الري؛ كروم عنب فليم اللابذرى؛ البراعم؛ نسبة المواد الصلبة الذائبة الكلية إلى الحموضة؛ العنقود؛ الحبات؛ الأنثوسيانين.

الإجهادات غير الحيوية، بما في ذلك الجفاف، تؤثر بشكل كبير على نمو وإنتاجية كروم العنب. تم تنفيذ تجربة حقلية على مدى ثلاثة مواسم نمو متتالية في تربة طميية رملية بمنطقة النوبارية في مصر. هدفت هذه الدراسة إلى فحص تأثير نقص الري على كفاءة استخدام المياه، والإنتاج، وجودة الثمار، والتركيب التشريحي للبراعم في كروم عنب فليم اللابذرى عمرها ٨ سنوات. تم تطبيق أربعة نظم ري من مرحلة ما قبل التزهير وحتى الحصاد، وهي: ١٢٥٪، ١٠٠٪، ٧٥٪، و ٦٠٪ من السعة الحقلية. أظهرت النتائج أن نسبة الوريقات الجافة داخل البراعم وطول الأجزاء الجافة في الوريقات زادت مع زيادة الإجهاد المائي في كلا الموسمين. كما أدى الري عند مستوى ٦٠٪ من السعة الحقلية إلى انخفاض في مؤشرات النمو، بما في ذلك طول الأفرع، وعدد الأوراق، ومساحة الورقة، وعدد العناقيد، وعدد الحبات، ومعامل انضغاط العنقود، ووزن وحجم ١٠٠ حبة، وحجم العصير، ونسبة خصوبة البراعم، مما أدى إلى انخفاض المحصول في كلا الموسمين. بالإضافة إلى ذلك، انخفض وزن العنقود بشكل معنوي تحت تأثير الإجهاد المائي فقط في