HortScience 60(2):172–181. 2025. https://doi.org/10.21273/HORTSCI18280-24

Impact of Irrigation Regimes on Growth and Postharvest Quality of Pomegranates (*Punica granatum* L.) under Conditions of Newly Reclaimed Land

Magdi A.A. Mousa, Adel D. Al-Qurashi, Omer H.M. Ibrahim, Kamal A.M. Abo-Elyousr, and Ahmed M.K. Abdel Aal
Department of Agriculture, Faculty of Environment Sciences, King Abdulaziz University, Jeddah 21589, Saudi Arabia

Abdel-Fattah M. El-Salhy
Department of Pomology, Faculty of Agriculture, Assiut University, Assiut, Egypt

Tarek K.H. El-Bolok and Mohamed A.H. Ali
Horticulture Research Institute, Agriculture Research Center, Giza, Egypt

Esmat F. Ali
Department of Biology, College of Science, Taif University, 11099, Taif 21944, Saudi Arabia; and Department of Floriculture, Faculty of Agriculture, Assiut University, Egypt

Eman A.A. Abou-Zaid
Department of Pomology, Faculty of Agriculture, Assiut University, Assiut, Egypt

Keywords. climate change, deficit irrigation, fruit quality, sustainable agriculture, water use efficiency

Abstract. **Farmers are encouraged to invest in crops that will grow and produce under the predicted climate change, such as global warming, limited water supplies, and drought-imposed water restrictions on agriculture. The drought-tolerant pomegranate (*Punica granatum* L.) is a promising horticulture crop that can be grown under arid conditions. To successfully implement irrigation management strategies in orchards, knowledge of plant responses to water deficits, tree shoot and fruit growth patterns, and irrigation management strategies that conserve water is required. The present study described the response of pomegranate trees of the Manfalouty variety to deficit irrigation under the local climate. The experiment was conducted during the 2020 and 2021 seasons. The experiment was carried out on a private farm in the Bani Uday district of Manfalouty, Assiut Governorate, Egypt. Eighteen trees with comparable strength and growth were chosen, free of elemental deficiency signs, planted at 3.5 × 3.5 m, with an age of 8 years. Three irrigation levels 50%, 75%, and 100% of the pomegranate tree's water standard were applied. With the randomized complete block design (RCBD), each treatment was used three times, with two trees in each iteration. Results revealed that applying irrigation at a rate of 75% enhanced fruit quality and yield, mitigated sun sting and cracking, and improved vegetative growth. Moreover, water use efficiency (WUE) was increased, which was reflected in the increase of the percentage of commercial and marketing fruits and decreased production costs when applying 75% of the water ration, which maintains soil and natural resources for sustainable agriculture.**

In tropical and subtropical regions, pomegranate trees are regarded as an important fruit crop due to their low cost of production for high-quality fruits, their economic viability for orchard establishment, and their good long-term storage quality. Furthermore, pomegranate trees may be planted in dry conditions and are resistant to drought (El-Salhy et al. 2023; Gómez-Bellot et al. 2024; Holland et al. 2009), making them appropriate for cultivation on recently reclaimed ground in Egypt. For many years, pomegranate farming was restricted to and considered a marginal crop in most of Egypt. It has been demonstrated to be efficient against a variety of maladies, including inflammatory problems, vascular diseases, and cancer, due to its abundance of different antioxidants and advantageous phytochemicals with polyphenolic qualities (Gómez-Bellot et al. 2024; O'Grady et al. 2014). Pomegranate locations are rapidly expanding for exportation purposes because of these advantageous qualities. Pomegranate chemical composition is highly influenced by cultivar type, climate, age, growing region, and agricultural practices (El-Salhy et al. 2015; Ozgen et al. 2008).

The pomegranate crop is one of the most important export crops in Egypt, where the percentage of Egyptian exports of pomegranates is ∼45% of the volume of production in Egypt as an average for the period (2015–19). The most significant pomegranate cultivar that has been successfully developed in upper Egypt is believed to be Manfalouty, particularly in the Assiut Governorate, which comes in second place in terms of both area and production after the Noubaria region. According to the Ministry of Agriculture's annual report (2022), the pomegranate area of the Assiut Governorate [10,889 feddan (fed.), a unit of area equal to 4200 m^2] was expected to be ∼13.08% of Egypt's total acreage (83,268) fed. Growers must consider a variety of elements to increase and optimize their yield, including irrigation, fertilization, propagation, and other horticultural techniques.

Fertilization and irrigation are the most effective cultural techniques for tree development, nutrient status, and fruiting, a claim that is still up for debate. Water is a valuable and limited resource in Egypt. As the population grows, one major obstacle to agricultural output is the availability of water for the agricultural industry. One way to make the most of this limited resource is to install an adequate and more efficient irrigation system. In orchards, water-saving irrigation methods like drip and micro sprinkler systems are widely used due to the requirement to minimize water usage while yielding high-quality fruit yields (Ntshidi et al. 2023).

One of the most crucial elements for biological function is water (Salisbury and Ross 1985). Important objectives include managing fruit, producing more, conserving irrigation water, and increasing water usage efficiency (Goldhamer et al. 1999). Water appears to be the material that fruit trees use most of all other materials (Chopade et al. 2001). In arid and semiarid areas, managing water is currently thought to be one of the largest problems facing all nations. In reality, there may be a water crisis by 2030 as a result of a 50% rise in global water consumption above current levels. In much of the world, the agricultural sector will use more than 70% of freshwater at the same time (Alcamo et al. 2000). The foundation of precision agriculture is the availability of exact data on soil, water, climate, socioeconomic factors, and political standards for crop production, sustainability, food security, and risk mitigation (Elwan and Barseem 2024). Crop-specific, water-saving irrigation systems that do not compromise crop output are needed for agriculture to manage water sustainably. Successful attempts to employ irrigation techniques and levels that increase WUE have been reported from all over the world. Water conservation is therefore crucial for agricultural growth, especially in dry and semiarid areas where high temperatures and a lack of water are the primary factors restricting plant growth and output. Climate change, water scarcity during droughts, and the growth of pomegranate farming in semiarid areas need growers to efficiently manage dwindling supplies of lower-quality water (Beelagi et al. 2023). Lack of water frequently results in decreased plant growth because it prevents the elongation of leaves and stems and lowers the plant's ability to absorb nutrients. Moreover, a lack of water has a detrimental effect on many plant species' inflorescence processes by lowering the fertility of newly created flowers. Finding methods to use water that is already accessible cheaply is therefore essential (Al-Humaid and Moftah 2005). Water is necessary in considerable volumes for cultivation on sandy, arid soils. This soil's low water-holding capacity leads to deep percolation beneath the root zone and quick infiltration (Beaumont 1993). Therefore, the main objective of the present work focused on the effects of different irrigation water regimes on yield and fruit quality of the Manfalouty pomegranate trees.

Materials and Methods

The Manfalouty pomegranate trees were raised in Banu Uday, Manfalout district, Assiut Governorate, Egypt, in a private orchard. The two seasons of 2020 and 2021 that followed each other were used for the study. Table 1 shows the parameters of the soil, which had a sandy loam texture. Furthermore, Table 2 examines the well water used for agricultural irrigation, according to Wilde et al. (1985).

Yearly fertilization of 15 m^3/fed. of organic manure (sheep manure) combined with 1.0 kg/tree of calcium superphosphate (15.5% P_2O_2) is applied to the trees in December. Furthermore, in February, April, and June, three equal dosages of 1.0 kg/tree potassium sulfate (48% K_2O) and 2.0 kg/tree ammonium sulfate (20.6% N) were added. For the purpose of this experiment, 18 healthy, 8-year-old trees that were planted 3.5 × 3.5 m apart under a drip watering system and showed no outward signs of nutrient deficiencies were selected. Throughout the two research seasons, the selected trees underwent the same horticultural practices with the exception of the varied treatments that were tried. Three replicates, each with two trees, were used in the RCBD setup for the treatments.

Irrigation treatments

In Assiut conditions, pomegranates were cultivated in sandy loam with drip irrigation, receiving standard procedures and 4, 4, 5, and 10 L per day per tree for the months of January through April, and 30, 50, 50, and 50 L per day per tree for the months of May, June, July, and August. Then, from September through December, trees were irrigated with 30, 10, 5, and 4 L per day per tree. Two Regulated deficit irrigations (or "RDI") plus a control treatment performed under Assiut conditions made up the irrigation treatments, as shown in Table 3.

Trees received twice-monthly irrigation in January and December. Also, they received four irrigations in February, whereas from March to November, they received daily irrigation.

In addition, Table 4 illustrates the monthly water consumption per feddan, considering that there are roughly 340 trees per fed. Over the course of the two study seasons, the following metrics were measured.

Vegetative growth parameters. In April, four primary branches that were practically identical in terms of development and distribution throughout the tree's four sides were chosen and labeled for the following vegetative measurements:

1. Shoot length (cm).
2. Leaf area (cm^2), was estimated as based on Ahmed and Morsy (1999).
3. Leaf relative chlorophyll was estimated by using a chlorophyll meter (Minolta SPAD, 502 plus).

Nutritional status, proline, and relative water content. Fifty mature leaves were selected at random from the spring shoots in the middle of September. Sulfuric acid and hydrogen peroxide were used in the digestion process, which was intended to ascertain the amounts of proline, N, P, and K, as well as relative water in the leaves (Wilde et al. 1985). Micro-Kjeldahl methods (Bremmer and Mulvaney 1982) were used to quantify nitrogen, whereas colorimetric and flame photometer methods (Jackson 1958) were used to detect potassium and phosphorus. In addition, the relative water content of the leaf was ascertained and estimated using Smart and Bingham's methodology (Smart and Bingham 1974), and the proline concentration of the leaf was computed using a dry weight basis in accordance with Singh et al. (1973).

Yield and its components. The yield/tree, which included burnt, cracked, and sound fruits, was noted after the fruit was picked. The average yield/tree (kg) was calculated by multiplying the average fruit weight by the total number of fruits on the tree. The defective fruits were separated into smaller groups to calculate the percentage of cracked and scorched fruits. Fruit cracking was determined as a percentage of all fruits collected by tallying the number of cracked and sunburned fruits.

Fruit quality. To determine the fruit quality, 10 randomly selected samples were taken from each tree. A digital vernier caliper (Model Dr-150, China) and digital balance (Model ACS-A9, General, China) were used to record the fruit's weight, length (cm), and diameter (cm). Using a hand refractometer, total soluble solids (TSS)% (Brix%) of arils juice was calculated, along with the percentage of arils and juice as well as the chemical fruit quality, such as TSS. In compliance with Association of Official Agricultural Chemists (AOAC 1995), the proportion of total acidity (expressed as citric acid) was also calculated. The ratio TSS/acidity was calculated using the measured parameter values. By titrating against 2,6-dichlorophenol-indophenol, vitamin C was quantified as mg/L ascorbic acid/100 mL juice (AOAC 1995). Reducing sugar was also calculated using the same techniques. Furthermore, the peel and juice's combined anthocyanin content was determined using the methodology of Onayemi et al. (2006). Five grams of peel or juice samples were ground up using a 10-mL mixture of 1.5 M HCl and ethanol (85:15 by volume). The samples were then covered and kept overnight at 4 °C in the refrigerator. Subsequently, a spectrophotometer (Model No. 1200, Unico, NJ, USA) was used to measure the absorbance of total anthocyanin at a wavelength of 535 nm after adding the solvent combination to each sample's solution to a volume of 50 mL.

Water use efficiency. This is how WUE was determined (Hussein 2004):

Table 1. Physical and chemical characteristics of the soil of the experimental site. The soil samples were taken as a mixture of hales depth of 0 to 90 cm.

Soil property	Value	Soil property	Value
Sand (%)	79.52	Organic matter (%)	0.53
Silt (%)	10.0	Total nitrogen (%)	0.16
Clay (%)	10.48	Mg (ppm)	194.4
Texture grade	Sandy loam	K (ppm)	15.60
Field capacity (%)	27.91	Na (ppm)	172.5
pH (1 to 2.5)	7.75	Cl (ppm)	667.4
Electrical conductivity ($dS \cdot m^{-1}$)	627 ppm	HCO_3 (ppm)	610.0
Ca (ppm)	376.0		

Table 2. Physical and chemical characteristics of irrigation water of the experimental site.

Electrical conductivity			Soluble cations (meq/L)				Soluble anions (meq/L)			
$dS \cdot m^{-1}$	ppm	pH	Ca	Mg	Na	K	CO_3	HCO_3	Cl	SO_4
1.18	755.2	7.15	7.26	3.07	1.1	1.7	—	3.2	5.11	2.02

Received for publication 23 Oct 2024. Accepted for publication 20 Nov 2024.
Published online 8 Jan 2025.
We extend our appreciation to the Deputyship for Research and Innovation, Ministry of Education in Saudi Arabia for funding this research work through the project number IFPIP: 188-155-2020 and King Abdulaziz University, DSR, Jeddah, Saudi Arabia.
M.A.A.M. is the corresponding author. E-mail: mamousa@kau.edu.sa.

Table 3. The quantity of water used for irrigation (in L/d/tree) for Manfalouty pomegranate trees in the 2020 and 2021 growing seasons.

	Month													
Treat.	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	T.L/tree/y	T.m^3/tree/y
T1 100%	4	4	5	10	30	50	50	50	30	10	5	4	7377	7.38
T2 75%	3.0	3.0	3.75	7.5	22.5	37.5	37.5	37.5	22.5	7.5	2.5	2.0	5532	5.53
T3 50%	2.0	2.0	2.5	5	15.0	25.0	25.2	25.5	15.0	5.0	2.5	2.2	3688	3.69

T = treatment; T.L/tree/y = total liter/tree/year; T.m^3/tree/y = total m^3/tree/year.

T1: Control treatment (water use).

T2: 75% of water use (regulated deficit irrigation "RDI").

T3: 50% of water use (regulated deficit irrigation "RDI").

Table 4. Irrigation scheduling program for Manfalouty pomegranate trees during the 2020 and 2021 growing seasons.

	Amount of irrigation water (m^3/fed.)		
Month	100% of water use (control)	75% of water use	50% of water use
January	2.72	2.04	1.36
February	5.44	4.08	2.72
March	52.70	39.53	26.35
April	102.011	76.50	51.00
May	316.200	237.15	158.10
June	510.00	382.50	355.00
July	527.00	395.25	263.5
August	527.00	395.25	263.5
September	306.00	229.50	153.00
October	105.400	79.05	52.70
November	51.00	38.25	25.50
December	2.72	2.04	1.36
Total amount of irrigation (m^3/fed./y)	2508.18	1881.14	1254.09

The formula for calculating the ratio of crop yield (Y) to the total amount of irrigation water (IR) used throughout the growing season is WUE = (kg)/IR (m^3).

Statistical analysis

According to Gomez and Gomez (1984) and Mead et al. (1993), the gathered data were statistically examined using the least significant difference values at 5% to ascertain the significance of the differences between the various treatment means.

Results

Effect of irrigation levels on vegetative growth and leaf nutrient contents

Parameters for shoots and leaves. Tables 5 and 6 present data on the effects of irrigation levels on the growth and vigor of Manfalouty pomegranate trees in 2020 and 2021. In addition to specific physical traits like relative chlorophyll and water content, the trees' vigor growth is indicated via length of shoots, area of leaves, or total leaf area/shoot measurements. The data unequivocally demonstrate that during the two research seasons, the outcomes adhered to a similar pattern.

The data displayed in the tables demonstrate a considerable increase in the shoot and leaf area at 75% or 100% irrigation as opposed to 50% water use (WU). When compared with previous irrigation levels, using 50% of the water applied resulted in much fewer growth attributes. Increasing the water application from 75% to 100% failed to demonstrate any discernible increase in these growth qualities. Overall, the data show a significant difference in most vegetative growth metrics across the various irrigation levels used in this study. The greatest value was noted as a result of 100% irrigation (check treatment). When irrigation was set at 50% of the water need as opposed to 100% of the WU, all evaluated vegetative attributes showed a substantial drop. These examined growth metrics did not significantly decrease when the water content was reduced to 75%.

When trees were irrigated by 50% and 75% of the water used, respectively, during the preliminary season, leaf area/shoot dropped by 18.43% and 2.83%, and by 18.16% and 2.43% in the subsequent season. Over the course of the two seasons under study, the corresponding decrement percentages of relative water were 15.68% and 2.03% and relative chlorophyll was 19.58% and 1.68% and 20.25% and 2.79%, respectively. It is possible to draw the conclusion that the vegetative growth of pomegranate trees has been positively and indirectly impacted by all irrigation levels used. Since a lack of water frequently inhibits the elongation of leaves and shoots and has a detrimental influence on photosynthetic efficiency, trees develop less quickly.

Leaf proline and nutrient contents. The data shown in Table 7 demonstrated how the degrees of irrigation affected the proline, N, P, and K % of the leaves of Manfalouty pomegranates in the 2020 and 2021 growing seasons. The data make it clear that there were no appreciable variations found between the outcomes for the two seasons under investigation.

In concern to the effect of different irrigation levels, the presented data in the tables show that the leaf content of macronutrients, N, P, and K were significantly increased when the irrigation level was 75% or 100% compared with 50% of the amount of WU. Raising the estimated water amount from 75% to 100% failed to show any significant increase in such macronutrients, whereas using 50% significantly decreased such nutrient contents compared with other irrigation levels used. The increment percentage of N, 32.5% and 35.83% and 24.46% and 25.17%; P, 31.13% and 37.26% and 31.53% and 40.09%; and K attained 23.15% and 26.85% and 24.56% and 27.19% due to irrigating by 75% or 100% compared with 50% in each of the two seasons under study, respectively.

Conversely, the leaf proline content significantly decreased due to irrigating via 75% or 100% of the WU compared with using 50% of WU. Raising the water amount from 75% to 100% failed to show any significantly decreased leaf proline content, but using 50% of WU significantly increased such studied

Table 5. Effects of irrigation water regimes (WR) on shoot length (cm), leaf area (cm^2), and leaf area/shoot (cm^2) of Manfalouty pomegranate trees in the 2020 and 2021 seasons.

	Shoot length (cm)			Leaf area (cm^2)			Leaf area/shoot (cm^2)		
Irrigation levels	2020	2021	Mean	2020	2021	Mean	2020	2021	Mean
50% WR	49.11 b	53.58 b	51.35 b	5.30 b	5.18 b	5.24 b	210.3 b	218.5 b	214.4 b
75% WR	56.25 a	59.14 a	57.69 a	6.02 a	6.04 a	6.03 a	250.5 a	260.5 a	255.35 a
100% WR	58.21 a	62.18 a	60.19 a	6.17 a	6.24 a	6.21 a	257.8 a	267.0 a	262.8 a
LSD at 5%	3.10	3.44		0.38	0.22		11.10	9.98	

Means followed by the same lowercase letters in the same column are not significantly different at $P < 0.05$ according to the least significant difference (LSD) test.

Table 6. Effect of irrigation water regimes (WR) on leaf relative water content and chlorophyll (SPAD value) of Manfalouty pomegranate trees in the 2020 and 2021 seasons.

	Chlorophyll (SPAD value)			Leaf relative water content %		
Irrigation levels	2020	2021	Mean	2020	2021	Mean
50% WR	47.91 b	47.44 b	47.68 b	77.13 b	75.68 b	76.41 b
75% WR	58.43 a	57.81 a	58.12 a	89.41 a	87.73 a	88.57 a
100% WR	60.84 a	58.85 a	59.85 a	92.22 a	90.48 a	91.35 a
LSD at 5%	2.51	2.23		3.98	3.85	

Means followed by the same lowercase letters in the same column are not significantly different at $P < 0.05$ according to the least significant difference (LSD) test.

trait compared with other irrigation levels used. The decrement percentage of leaf proline attained 5.34% and 5.82% and (6.77% and 7.43% due to irrigating the pomegranate trees by 75% or 100% of the WU compared with 50% of WU during the two studied seasons, respectively. It is possible to draw the conclusion that increasing irrigation by 75% will boost tree vigor and development while also increasing water efficiency. In addition, it lowers production costs and is particularly helpful in reducing water usage.

Irrigation levels' impact on yield components

The information provided in Table 8 demonstrated how the amount of irrigation affected the Manfalouty pomegranate trees' yield components in the 2020 and 2021 growing seasons. The data clearly show that during the two seasons under study, the results followed a similar trend.

As compared with 50% WU, the yield components improved significantly when the irrigation level was set at 75% or 100%, according to the data shown in the table. When compared with other irrigation levels, using 50% of the water amount resulted in significantly lower yield components. Increasing the water amount from 75% to 100% did not provide any discernible gain in yield components.

Overall, the data shown exhibit a significant difference in most yield component measures across the various irrigation levels used in the present investigation. The highest value was noted as a result of 100% irrigation (check treatment). When irrigation was set at 50% of the water consumption as opposed to 100% of the WU, all examined yield attributes showed a significant impact. In other words, data showed that irrigation at 75% or 100% of the WU greatly enhanced fruit cracking and yield/tree and significantly lowered the proportion of sunburned fruit. This, in turn, led to a significantly higher percentage of marketable fruit when compared with irrigation at 50% of the WU. The highest yield/tree and marketable fruit percentage was achieved by using 100% of the water, whereas the lowest values were obtained by using 50% of the water usage. Then, the decreased percentage of yield/tree due to reducing the used water requirement under irrigation by 100% of the water requirement was attained (20.13% and 6.81% and 18.28% and 5.23%) due to irrigating by 50% or 75% of WU compared with 100% of WU during the two studied seasons, respectively. The corresponding decrement percentage of splitting fruit was 13.31% and 8.13% and 10.16% and 8.20% during the two studied seasons, respectively. In contrast, the increment percentage of sunburned fruit was 41.81% and 4.06% and 38.08% and 4.61%, then, the decrement percentage of marketable fruit attained 3.10% and 0.01% and 2.44% and 0.0% due to irrigating via 50% or 75% of WU compared with 100% of WU during the two studied seasons, respectively. We may conclude that the output of pomegranate trees has been positively and indirectly impacted by all of the irrigation levels that have been used. Because a lack of water can hinder the elongation of leaves and shoots and have a detrimental influence on photosynthetic efficiency, it is common for trees to grow less. As a result, there is a decrease in the amount of nutrients that are stored, bud formation, and yield output.

Irrigation levels' impact on fruit quality

Fruit's physical characteristics. The effects of varying irrigation levels were demonstrated by the data in Tables 9 and 10, which demonstrated that when irrigation was at 75% or 100% as opposed to 50% of the total WU, the physical qualities of the fruit were greatly improved. In general, view presented data exhibit a marked variation of physical fruit traits among the different irrigation levels used in this study. The highest value was recorded due to irrigating at 100% level (check treatment). All studied physical fruits except peel anthocyanin content significantly decreased when irrigation level was 50% of WU compared with 100% of WU. Applying 50% of WU significantly increased the peel anthocyanin content compared with using 75% or 100% WU.

Subsequently, the percentage of fruit weight that decreased when the water demand was reduced under 100% water usage for irrigation was obtained (27.96% and 8.65% and 27.89% and 7.59%) when the water requirement was reduced under 50% or 75% irrigation as opposed to 100% WU during the two seasons under study, respectively. For the two seasons under study, the corresponding decrement percentage of arils was 8.26% and 2.99% and 6.84% and 1.77%, whereas the corresponding decrement percentage of juice volume was 11.85% and 5.62% and 11.55% and 5.55%. Conversely, the increase in peel anthocyanin percentage was achieved (10.46% and 3.94% and 10.77% and 3.42%) as a result of irrigating using 50% or 75% of WU as opposed to 100% of WU

Table 7. Effect of irrigation water regimes (WR) on the content of N, P, K, and proline in leaves of Manfalouty pomegranate trees 2020 and 2021.

	N%			P%			K%			Proline content		
Irrigation levels	2020	2021	Mean	2020	2021	Mean	2020	2021	Mean	2020	2021	Mean
50% WR	1.2 b	1.39 b	1.34 b	0.212 b	0.222 b	0.217 b	1.08 b	1.14 b	1.11 b	15.49 a	14.65 a	15.07 a
75% WR	1.59 a	1.73 a	1.66 a	0.278 a	0.292 a	0.285 a	1.33 a	1.42 a	1.38 a	14.41 b	13.61 b	14.01 b
100% WR	1.63 a	1.74 a	1.69 a	0.291 a	0.311 a	0.301 a	1.37 a	1.45 a	1.41 a	14.27 b	13.54 b	13.91 b
LSD at 5%	0.06	0.04		0.018	0.020		0.04	0.04		0.41	0.36	

Means followed by the same lowercase letters in the same column are not significantly different at $P < 0.05$ according to the least significant difference (LSD) test.

Table 8. Effects of irrigation water regimes (WR) on production (kg/tree), fruit cracking percentage, sunburn percentage, and marketable percentage of Manfalouty pomegranate trees in 2020 and 2021 seasons.

	Yield kg/tree			Fruit cracking %			Sunburn %			Marketable %		
Irrigation levels	2020	2021	Mean	2020	2021	Mean	2020	2021	Mean	2020	2021	Mean
50% WR	22.49 b	24.11 b	23.3 b	10.31 b	9.56 b	9.94 c	15.31 a	13.29 a	14.3 a	74.32 b	77.15 b	75.74 b
75% WR	26.55 a	28.35 a	27.45 a	10.89 b	10.11 b	10.5 b	11.35 b	10.10 b	10.73 b	77.26 a	79.74 a	78.37 a
100% WR	28.62 a	30.10 a	29.36 a	11.62 a	10.79 a	11.21 a	10.88 b	9.65 b	10.28 b	77.50 a	79.47 a	78.49 a
LSD at 5%	2.33	2.68	1.95	0.58	0.63	0.45	0.69	0.56	0.48	1.83	1.62	1.26

Means followed by the same lowercase letters in the same column are not significantly different at $P < 0.05$ according to the least significant difference (LSD) test.

Table 9. Effect of irrigation water regimes (WR) on fruit weight (g), length (cm), and diameter (cm) of Manfalouty pomegranate trees in 2020 and 2021 seasons.

	Fruit wt (g)			Fruit length (cm)			Fruit diam (cm)		
Irrigation levels	2020	2021	Mean	2020	2021	Mean	2020	2021	Mean
50% WR	239.4 c	280.5 c	259.95 c	6.68 c	7.02 c	6.85 c	6.91 c	7.25 c	7.08 c
75% WR	302.3 b	357.9 b	330.1 b	7.53 b	7.73 b	7.73 b	7.79 b	8.18 b	7.99 b
100% WR	331.2 a	389.1 a	360.15 a	8.12 a	8.34 a	8.23 a	8.46 a	8.86 a	8.66 a
LSD at 5%	8.85	8.29		0.19	0.12		0.16	0.16	

Means followed by the same lowercase letters in the same column are not significantly different at $P < 0.05$ according to the least significant difference (LSD) test.

Table 10. Effect of irrigation water regimes (WR) on peel content of anthocyanins (mg/100 g), arils percentage, and juice volume (mL) of Manfalouty pomegranate fruits in 2020 and 2021 seasons.

	Anthocyanin in peel (mg/100 g)			Arils %			Juice volume (mL)		
Irrigation levels	2020	2021	Mean	2020	2021	Mean	2020	2021	Mean
50% WR	53.97 a	52.90 a	53.44 a	50.21 b	51.62 b	50.92 b	55.8 c	55.2 c	55.5 c
75% WR	50.55 b	48.84 b	49.69 b	53.67 a	54.94 a	54.31 a	59.9 b	59.2 b	59.55 b
100% WR	49.23 b	48.38 b	48.81 b	54.93 a	55.63 a	55.28 a	62.1 a	63.1 a	62.6 a
LSD at 5%	1.42	1.39		1.65	1.58		1.56	1.38	

Means followed by the same lowercase letters in the same column are not significantly different at $P < 0.05$ according to the least significant difference (LSD) test.

during the two seasons under study. One can infer that enhancing the irrigation system by 75% of the total water used (5.53 m^3/tree/year) will enhance the fruit's physical attributes. In addition, it reduces manufacturing costs, and the amount of water needed, and it was highly beneficial for water conservation. Furthermore, to stop rising water tables and salinity in the root zone.

Chemical juice constituents. Results for TSS %, reducing sugar %, acidity %, TSS/acidity, anthocyanin concentrations in juice, vitamin C, and water usage efficiency of pomegranate fruits are displayed in Figs. 1–7. Chemical juice components had a substantial impact at the various irrigation levels that were examined. Increasing the amount of water used from 75% to 100% did not result in a discernible rise or fall in these juice ingredients.

According to data, using half as much water (WU) boosted TSS while lowering the juice's sugar and anthocyanin content. Conversely, when compared with using 75% or 100% WU, such an irrigation level greatly reduced the overall acidity and vitamin C concentrations. Next, the increased percentage of TSS resulting from irrigating at 75% or 100% of WU as opposed to using 50% of WU throughout the two seasons under study was obtained (3.21% and 4.30% and 3.43% and 4.40%, respectively). During the two seasons under study, the corresponding increased percentages for decreasing sugar were 3.91% and 5.43% and 3.38% and 5.51%, respectively, and for juice anthocyanin content, they were 6.65% and 11.20% and 7.15% and 11.53%. Conversely, the reduction in the percentage of total acidity resulting from irrigating using 50% or 75% of water regime (WR) yielded results of 7.20% and 1.50% and 5.83% and 0.0% when irrigating using 50% or 75% of WU as opposed to 100% of WU throughout the two seasons under study. In the two seasons under study, the corresponding vitamin C decrement percentages were 4.43% and 0.05% and 4.37% and 1.21%, respectively.

In addition, the results shown in Fig. 7 demonstrated a significant drop in water consumption efficiency when the irrigation level was set at 75% or 100% as opposed to 50% of the total amount of WU. When compared with other irrigation levels, using 50% of WU resulted in a considerable gain in WUE. However, increasing the amount of water used from 75% to 100% considerably decreased WUE. Next, the increased percentage of WUE owing to irrigating with 50% or 75% of WU compared with 100% of WU throughout the two examined seasons, and 59.52% and 24.05% due to irrigating with 100% of WU, were reached. It is possible to draw the conclusion that using 50% or 75% less water has a positive and indirect impact on WUE, given that a water shortage frequently results in increased WUE.

Principal component analysis. Principal component analysis (PCA) was performed to visualize the relationship between the effect of different irrigation levels on the growth, yield, and fruit quality of Manfalouty pomegranate trees (Fig. 8). The PCA showed a clear separation of the effects of the different treatments on the parameters. The variables with narrow angles are close together, reflecting their relatively large positive correlation. On the other hand, the variables in the third quadrant that have a large angle with the variables in the first quadrant have a negative correlation. In addition, the data showed that 100% IR has a positive relation with most characteristics but a negative correlation with proline and TSS and WUE, whereas 75% IR was in the second quadrant and it is close to the directions defined by shoot length, leaf area, leaf water content, yield, fruit cracking, juice volume, fruit weight, fruit diameter, vitamin C,

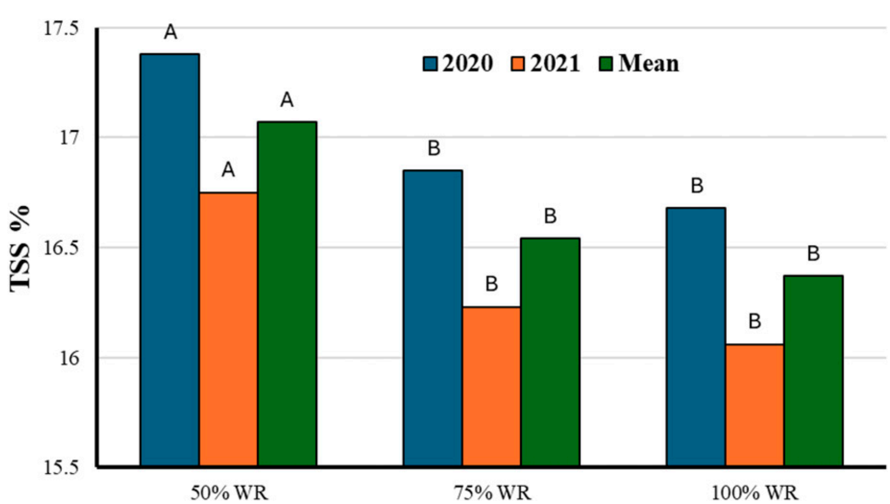

Fig. 1. Impact of irrigation water regimes (WR) on fruit total soluble solids percentage (TSS%) of Manfalouty pomegranate during 2020 and 2021 seasons. Different letters denote significant differences at $P < 0.05$ according to least significant difference test.

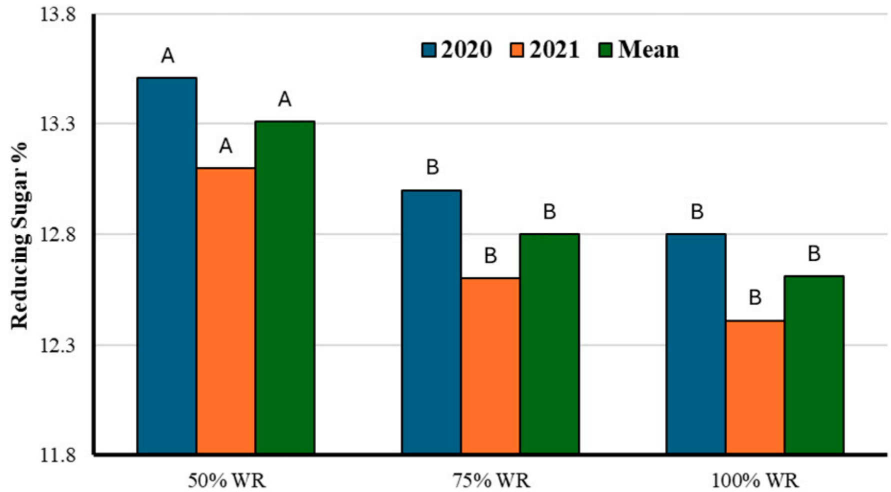

Fig. 2. Impact of irrigation water regimes (WR) on fruit reducing sugar% of Manfalouty pomegranate during 2020 and 2021 seasons. Different letters denote significant differences at $P < 0.05$ according to least significant difference test.

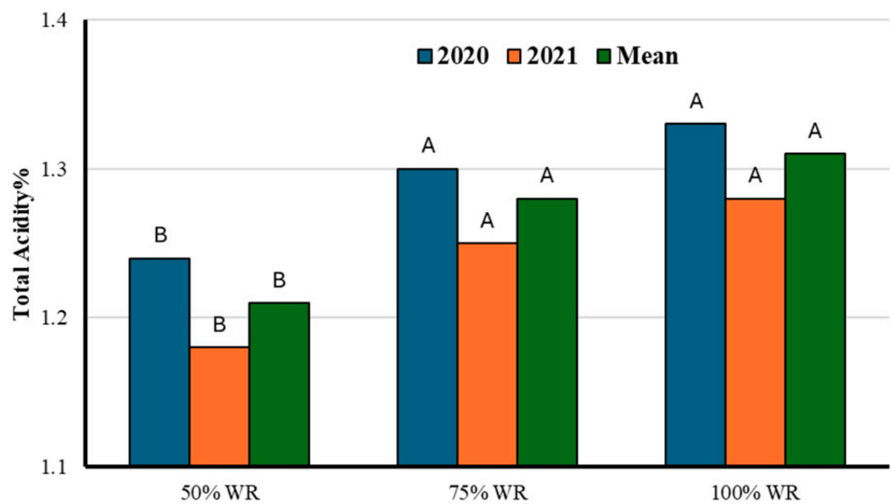

Fig. 3. Impact of irrigation water regimes (WR) on fruit acidity% of Manfalouty pomegranate during 2020 and 2021 seasons. Different letters denote significant differences at $P < 0.05$ according to least significant difference test.

Marketable %, N%, P%, K%, and arils % but not far from WUE, TSS, and proline. Conversely, 50% IR fell into the third quadrant, was negatively correlated with most development variables, and was near the directions indicated by sunburn, proline%, TSS, and WUE.

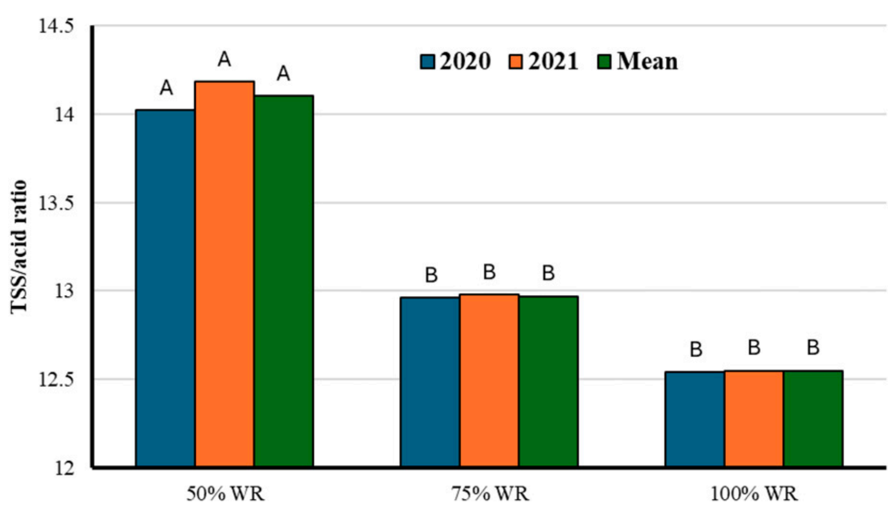

Fig. 4. Impact of irrigation water regimes (WR) on fruit total soluble solids (TSS)/acid ratio of Manfalouty pomegranate during 2020 and 2021 seasons. Different letters denote significant differences at $P < 0.05$ according to least significant difference test.

Discussion

Drought is one of the biggest and most important problems influencing agricultural productivity; it is happening increasingly often all over the world. One of the main obstacles to sustained fruit production in important growing regions of arid and semiarid regions is the availability of sufficient water for irrigation (Ntshidi et al. 2023; Sarkar et al. 2024). Overall, the study's findings showed that different irrigation schedules enhanced the pomegranate plants' vegetative traits and nutritional quality. Systems of irrigation have a major impact on fruit crop development, output, and quality. When drip irrigation was used instead of flood irrigation, growth and fruiting characteristics increased. Maintaining the proper moisture content in the tree's active root zone by drip irrigation minimizes nutrient loss as the water moves through the lowest soil layer. In addition, when compared with a standard flood watering system, drip irrigation reduces plant root problems, which enhances tree development, productivity, and fruit quality (Beelagi et al. 2023; Granatstein and Sánchez 2009; Mousa et al. 2013).

Water stress may affect shoot growth because it can decrease the amount of cytokinin transferred from roots to shoots and increase the amount of abscisic acid in leaves. The disrupted hormone balance resulted in a reduction of both cell proliferation and leaf expansion. These results align with the findings of El-Iraqy et al. (2006) on guava and Khattab et al. (2010) on pomegranates, which reported that increasing irrigation rates significantly increased the vegetative growth characteristics.

The right amount of moisture must be in the soil for fruit trees to produce fruits with maximal cell division and cell expansion. Typically, flood irrigation requires more water than a modified irrigation system. Moreover, drip irrigation raised the concentration of essential nutrients like N, P, K, and Zn in comparison with conventional flood irrigation, resulting in a high production and quality fruit. Furthermore, fruit output, quality, and the effectiveness of fertilizer application are all significantly impacted by irrigation. Reduced nutrient uptake from the soil caused by suitable irrigation measures degrades fruit quality (Hutton et al. 2007; Quiñones et al. 2007). A contemporary irrigation system was used to achieve maximum fertilizer uptake and minimal nutrient leaching (Shirgure and Srivastava 2013).

The same findings were seen in our study: Manfalouty pomegranate leaves with greater nutritional contents (N, P, and K) were found in trees grown at 75% or 100% of the projected water content as opposed to trees cultivated at 50% of the expected water content. Reduced leaf element levels with decreased irrigation amounts are explained by a significant drop in transpiration rates as well as compromised active transport and membrane permeability, which lowers the ability of the roots to absorb nutrients. The improvement in tree growth under 75% or 100% of the quantity of WU led to an increase in the yield per tree. Our findings are consistent with the

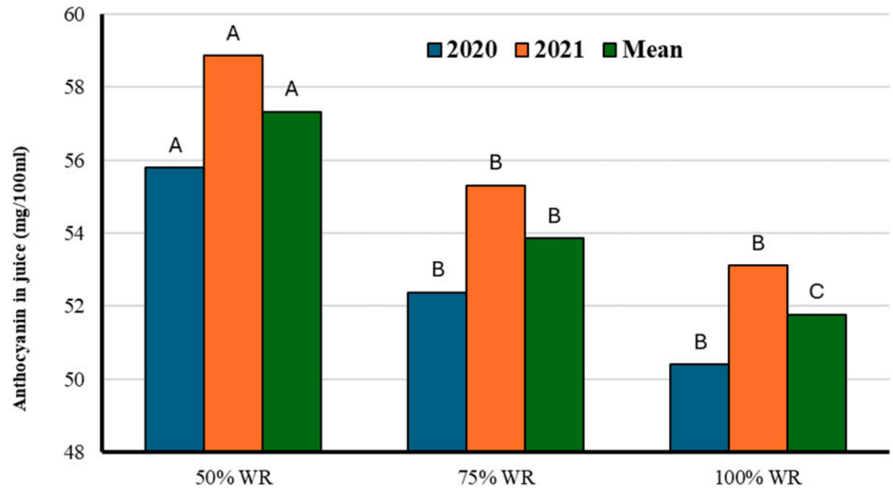

Fig. 5. Impact of irrigation water regimes (WR) on fruit juice content of anthocyanins (mg/100 mL) of Manfalouty pomegranate during 2020 and 2021 seasons. Different letters denote significant differences at $P < 0.05$ according to least significant difference test.

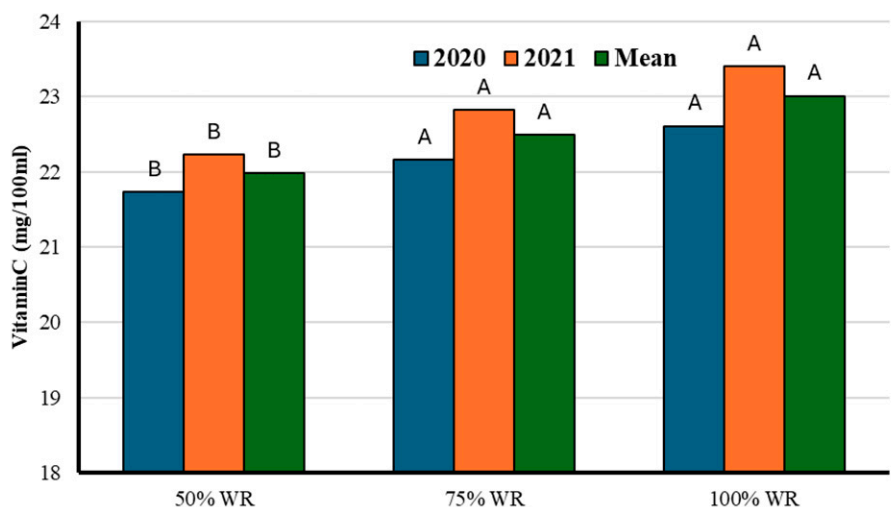

Fig. 6. Impact of irrigation water regimes (WR) on fruit content of vitamin C (mg/100 mL) of Manfalouty pomegranate during 2020 and 2021 seasons. Different letters denote significant differences at $P < 0.05$ according to least significant difference test.

findings of Khattab et al. (2011), Abd-Ella (2011), El-Bolok et al. (2022), and El-Salhy et al. (2023), which showed that irrigation regimens had a substantial impact on the shoot length, number of leaves, and leaf area of pomegranates.

Compared with conventional flood irrigation, drip irrigation preserves a consistent supply of moisture, improving tree output (Mankotia and Sharma 2024; Raza et al. 2016). When compared with trees planted with 50% of WU, the trees grown with 75% of WU produced the highest yield and most marketable fruits, increasing by roughly 18.05% and 17.59% and 3.96% and 3.36% over the course of the two examined

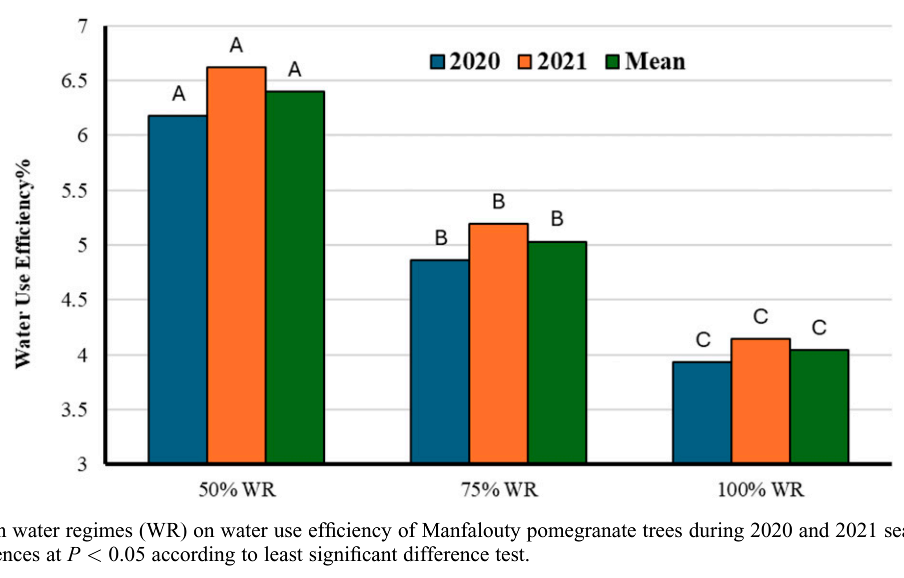

Fig. 7. Impact of irrigation water regimes (WR) on water use efficiency of Manfalouty pomegranate trees during 2020 and 2021 seasons. Different letters denote significant differences at $P < 0.05$ according to least significant difference test.

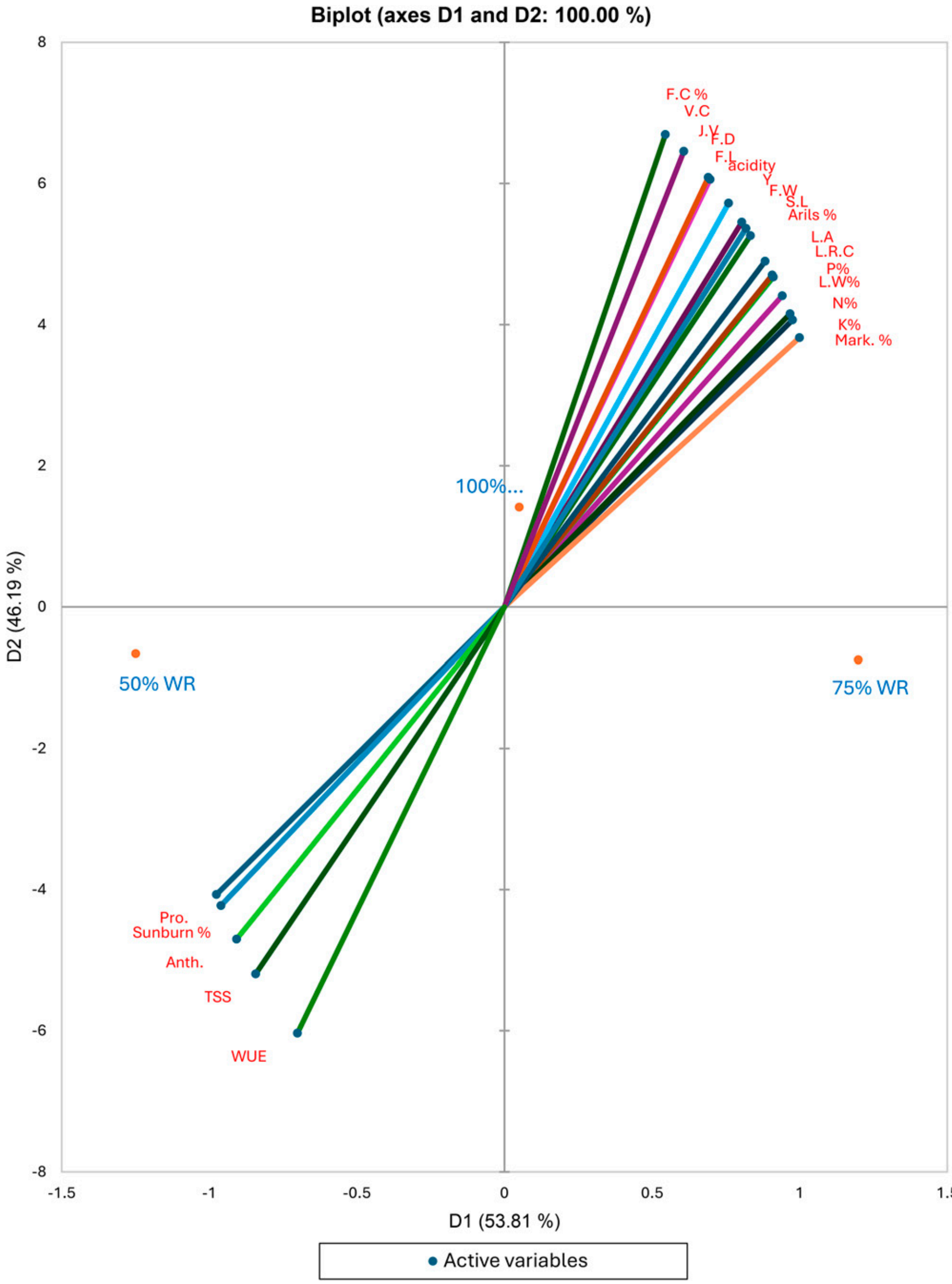

Fig. 8. Principal component analysis of various indicators in growth, yield, and fruit quality of Manfalouty pomegranate trees under different irrigation levels. SL = shoot length (cm); LA = leaf area (cm^2); LW = leaf water content; Pro. = proline; Y = yield kg; FC = fruit cracking %; JV = juice volume; FW = fruit weight; FD = fruit diameter; VC = vitamin C; Mark. = Marketable %; TSS = total soluble solids; WUE = water use efficiency; LRC = Leaf relative chlorophyll (SPAD value); FL = fruit length (cm); Anth = Anthocyanin in peel (mg/100 g); WR = water regime.

seasons, respectively. These outcomes are consistent with what was published by Abd El-Rahman (2010), Khattab et al. (2011), and El-Salhy et al. (2023). They discovered that when soil moisture levels were lower, Manfalouty pomegranate fruit shattering decreased. They also observed that the highest moisture availability produced the highest yield. Conversely, the least irrigation amount produced the fewest fruits El-Bolok et al. (2022).

In our study, 75% of WR reduced WU by up to 24% without a reduction in tree growth and productivity compared with using 100%. The trees under 75% of WU produce a higher yield and have better WUE. The production of fruit trees is directly affected by irrigation because irrigation has an impact on nutrient uptake and tree development. According to El-Halaby (2015), 75% of the anticipated water requirements increased soil moisture and aeration, which in turn increased growth, photosynthetic rate, and glucose translocation, all of which boosted tree fruiting. These findings are consistent with research conducted on various pomegranate cultivars by Dinc et al. (2018) and Nasrabadi et al. (2019); these studies found that the highest irrigation level was associated with the lowest levels of fruit acidity and leaf proline, whereas lowering the irrigation level was associated with an increase in soluble carbohydrate content. According to our findings, adding 50% more WU to juice resulted in a considerable increase in TSS while lowering its sugar and anthocyanin content. However, when compared with 75% or 100% WU, this irrigation level significantly reduced the total acidity and vitamin C contents. This may be because of the dilution that occurs when a larger fruit weight is irrigated at 75% or 100% of the water used, which is not always compensated by an increase in the amount of carbohydrates produced by photosynthesis. As part of the stress response, water stress increases secondary metabolism, specifically anthocyanin production (Kevin et al. 2009). The most crucial quality attributes, including size, firmness, color, sugar concentration, titratable acidity, sugar/acid ratio, dry matter concentrations, and volatile aromas, can all be altered by water stress. Food that receives insufficient irrigation often has more TSS, in part because of a higher dry matter content, although water stress could negatively affect plant growth and productivity (Gómez-Bellot et al. 2024). The comparable results demonstrated that, in similar climatic conditions, trees receiving more frequent irrigation used more water than trees receiving less frequent irrigation (El-Salhy et al. 2023; Khattab et al. 2011).

Conclusion

One may draw the conclusion that increasing irrigation by 75% of the total amount of water will improve fruit quality, vegetative development, and water usage efficiency. It also lowers production costs and the amount of water required, and it is very helpful in conserving water and lowering pollution levels in the environment, in addition to preventing root zone salinity and rising water tables.

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