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Sustainable Deficit Irrigation Technique to Enhance "KEITT" Mango Productivity in a Semi-Arid Climate Region

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Abstract: Water scarcity necessitates the implementation of various strategies to manage irrigation processes, aiming to optimize water usage for sustainable development, particularly in Semi-Arid regions. This research investigates the impact of using a sustainable deficit irrigation (SDI) technique alongside a drip irrigation system on the efficiency of water use and the growth and productivity of "KEITT" mango trees. The experiment examined four levels of irrigation requirements (IR) at 50%, 60%, 75% and 100%, using four different dripper spacing distances (60, 50, 40 and 30 cm). The average tree productivity during the 2022 season was 26.060, 24.100, 25.740 and 24.330 kg/tree, respectively, while in the 2023 season, it was 25.940, 24.760, 25.250 and 24.380 kg/tree. The average water use efficiency (WUE) values were 4.950, 3.880, 3.240 and 2.320 kg/m³ for the 50%, 60%, 75% and 100% IR treatments, respectively. The results indicated no significant differences in the growth and productivity of the mango crop across different irrigation levels. It was found that irrigating at 50% IR achieved the highest water use efficiency, saving more than 3500 m³ of water per fedden per season. These findings suggest that policymakers can adopt sustainable deficit irrigation techniques to enhance WUE without compromising crop productivity.

1 Introduction

Globally, the agricultural sector consumes over two-thirds of the earth's freshwater resources (Qiang Chai et al 2016). Arid and semi-arid regions, which cover more than 40% of the earth's surface, are land to many people who depend heavily on agriculture to meet their basic food needs. However, these areas face significant challenges due to limited and scarce water resources, frequent droughts, and insufficient rainfall. These factors present major obstacles to the sustainability of agriculture and development in these regions (Golla 2021). Consequently, irrigation plays a crucial and central role in supporting agricultural production and sustainable development in arid and semi-arid regions. The prolonged impact of limited and increasingly scarce water resources on the agricultural sector is expected to be substantial, with predictions that agricultural production could decline by up to 60% by 2050 in some countries with arid and semi-arid climates (Hejazi et al 2023).

For these reasons, irrigation management is essential and inevitable as an optimal solution for conserving irrigation water and maximizing the benefit of each unit of water used. Sustainable deficit irrigation, a key irrigation management strategy, involves supplying crops with less water than their full irrigation needs throughout the growing season and across all phenological stages. This approach reduces the amount of water used in production, enhances water use efficiency, and improves product quality without significantly impacting the quantity and quality of the yield (Lipan et al 2021). In this context, a field experiment was conducted over three seasons on mango trees to evaluate the impact of sustainable deficit irrigation strategies on fruit production, quality, and growth. Three levels of irrigation requirements (75%, 50%, and 33% ETc) were tested, along with a control treatment of 100% ETc. The results indicated that the 50% ETc treatment was the most effective, yielding the highest production and water use efficiency (Zuazo et al 2011).

Similarly, withholding irrigation entirely during the flowering stage for mango trees resulted in better flowering induction for the Tommy Atkins mango cultivar (Faria et al 2016). Mango trees are drought-tolerant, and techniques such as controlled deficit irrigation and partial root-zone drying positively impact fruit quality and enhance water use efficiency (Spreer et al 2009).

Regulated deficit irrigation at 50% ETc for Tommy Atkins mango trees maintains yield, fruit quality, and water use efficiency during different stages of fruit growth (Santos et al 2016). When mango trees were irrigated with three different levels of water—100%, 85%, and 70% of ETc—regulated deficit irrigation, which induced water stress, and curtailed excessive vegetative growth while promoting flowering and increasing production. These irrigation levels did not affect the acidity, vitamin C content, weight, or size of the ripe mango fruits. The 85% of ETc irrigation treatment was found to be the most effective in enhancing most of the quality characteristics of the mango fruits (Shaban et al 2020).

Drip irrigation is recognized as a critical component in optimizing water use for mango cultivation, and is considered the most efficient irrigation system (Ghosh et al 2022). It enhances water and nutrient utilization, leading to improved fruit quality and overall productivity. Compared to other methods, drip irrigation significantly increases crop yields by 28.92%, 14.55%, 8.03%, 2.32%, and 5.17% over flooding, border, furrow, sprinkler, and micro-sprinkler irrigation, respectively (Yang et al 2023). Therefore, this study aims to manage irrigation water using a sustainable deficit irrigation technique to rationalize irrigation water, maximize mango productivity and enhance water use efficiency using a drip irrigation system in Wadi El Natroun.

2 Materials and Methods

2.1 Experimental site

The experiment was conducted in a mango orchard located in the Wadi El-Natroun area (Latitude 30.2932750 N, Longitude 30.303820 E) in the Behera Governorate, within the northeastern Western Desert of Egypt, as shown in **Fig 1**. Wadi El-Natroun is a significant agricultural area that relies heavily on groundwater for irrigation. This reliance makes it an ideal location to study the impact of sustainable deficit irrigation techniques on water use efficiency and crop productivity.

Utilizing an auger machine, random soil samples were retrieved from different sectors and depths ranging from 0 to 40 cm, 40 to 80 cm, and 80 to 120 cm. The physical and chemical properties of these soil samples are presented in **Tables 1 and 2**.

The mango trees received irrigation with water sourced from a deep artesian well. Regular analyses were conducted during the growing season. **Table 3** presents the average results of these analyses.

The evapotranspiration data for the years 2022 and 2023, as shown in **Table 4**, were sourced from the Central Laboratory for Agricultural Climate of the Egyptian Ministry of Agriculture. This information was collected from the nearest agricultural meteorological station to the research site.

2.2 Irrigation system

The drip irrigation system was employed as a locally suitable irrigation method for calcareous soils and specifically adapted for irrigating mango trees. This system comprises the following components:

2.2.1 Pump and control unit

Within the farm premises lies a deep underground well, measuring 200 m in depth and 10 inches in diameter. The static water level within the well stands at 120 m, with a drawdown of 3 m, and a safe flow rate of 120 m^3/h. This well is equipped with a pumping unit, comprising an electric submersible pump positioned at a depth of 150 m within the well. The pump boasts a capacity of 60 hp and can deliver a flow rate of 85 m^3/h.

Fig 1. The experimental site in Wadi el-Natroun, Behera governorate, Egypt

Table 1. Soil physical characteristics of the experimental site

Depth (cm)	Texture class	Sp (%)	F.C (%)	W.P (%)	B.d (gm/cm^3)
0-40	Loamy sand	20	10.11	4.11	1.44
40-80	Loamy sand	22	10.18	4.05	1.48
80-120	Loamy sand	23	10.22	3.95	1.51

Table 2. Soil chemical analysis of the experimental site

Depth (cm)	Caco$_3$ (%)	pH	Ec (ds/m)	TDS (ppm)	Ca^{++}	Mg^{++}	K^+	Na^+	Cl^-	HCO_3^-	$SO_4^=$
					cation (meq/l)				anion (meq/l)		
0-40	28.5	7.9	1.72	1100	1.3	5.11	0.74	6.57	10.95	1.3	1.47
40-80	26.5	8.1	2.03	1300	4.5	4.91	0.72	10.5	16.98	1.1	2.55
80-120	27.4	8.1	2.15	1376	5.79	3.77	0.23	10.8	18.44	0.88	1.27

Table 3. Characteristics of chemical analyses of irrigating water

PH	Ec (ds/m)	TDS (ppm)	Ca^{++}	Mg^{++}	K^+	Na^+	Cl^-	CO_3^{-2}	HCO_3^-	$SO_4^=$
			cation (meq/l)				anion (meq/l)			
7.9	0.95	608	0.72	1.1	0.15	6.55	5.23	0.00	2.20	1.09

Table 4. Evapotranspiration data for the seasons 2022 and 2023 in the Wadi El Natroun region

Months	ETo for 2022 (mm/day)	ETo for 2023 (mm/day)
January	2.26	2.54
February	3.03	3.01
March	4.22	4.78
April	7.81	6.21
May	8.65	8.00
June	9.35	8.71
July	9.28	9.16
August	8.60	8.17
September	7.51	7.12
October	5.09	4.98
November	3.26	3.43
December	2.54	2.49
Average	5.97	5.72

Positioned directly above the well is the control station, which encompasses the components illustrated in **Fig 2**.

2.2.2 Irrigation network

The primary pipeline comprises PVC pipes with a 160 mm outer diameter and operates under a pressure of 6 bar, facilitating the transfer of irrigation water from the control station to the sub-main line. Sub-main lines, on the other hand, are constructed using PVC pipes with a 125 mm outer diameter and operate under a pressure of 6 bar, conveying irrigation water from the main line to the manifolds and lateral lines. Manifolds, constructed with PVC pipes boasting a 75 mm diameter and operating under a pressure of 6 bar, distribute irrigation water from the sub-main lines to the drip lines.

2.2.3 Drippers lines

The drip lines are composed of polyethylene hoses with a 16 mm outer diameter and a thickness of 1.1 mm. These lines feature emitters with varying distances between them, including 60 cm, 50 cm, 40 cm, or 30 cm. To regulate the irrigation water volume according to the experiment's design, the G.R long path emitter was used, delivering a discharge of 4 liters per hour at a pressure of 1 bar. **Fig 3** displays the layout of the drip irrigation system network.

2.3 Mango trees

The research centered on 12-year-old mango trees belonging to the 'KEITT' cultivar (Mangifera indica. cv. “KEITT”), meticulously grafted onto Sukari rootstock and systematically arranged with planting spacings of (3m*2m) on a grid. Careful selection ensured a high level of uniformity in terms of size, age, and overall appearance among the trees. Throughout the growing season, these trees received attentive care, following recommended horticultural practices diligently. This included a structured pruning regimen, proactive measures for pest and disease control, and a consistent fertilization program encompassing all necessary nutrients for optimal growth and productivity. These practices were meticulously implemented to maintain a consistent and homogeneous agricultural environment for the trees. The crop coefficient (Kc) values for mango trees are detailed in **Table 5** according to Allen et al (1998). The Kc values for the mango crop are 0.5 during the initial stage, 0.7 during the mid-stage, and 0.6 during the end stage of growth.

2.4 Irrigation requirement calculations

2.4.1 Water requirement

Water requirements were determined by utilizing the reference evapotranspiration data provided in **Table 4** alongside the mango crop coefficient outlined in **Table 5**. This calculation was performed following the equation proposed by Allen et al (1998):

$$\mathrm{ETc} = \mathrm{ETo} \times \mathrm{Kc} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Where ETc represents crop evapotranspiration (mm/day), ETo represents reference evapotranspiration (mm/day), and Kc represents crop coefficient (Without units).

2.4.2 Leaching requirements

Leaching requirements for mango trees were computed using the following equation as proposed by Doorenbos and Pruitt (1977):

$$\mathrm{LR} = \frac{\mathrm{EC_{iw}}}{2\ \mathrm{EC_e}} \times 100 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Where L.R represents leaching requirements (%), Ec_{iw} represents the salt concentration in irrigation water (ds/m) taken from **Table 3**, and Ec_e represents the average concentration of salts in the extract of soil dough saturated with water (ds/m) taken from **Table 2**.

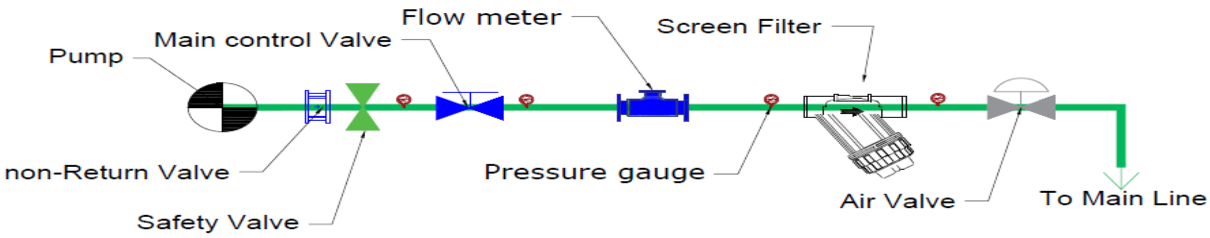

Fig 2. The control station for drip irrigation system

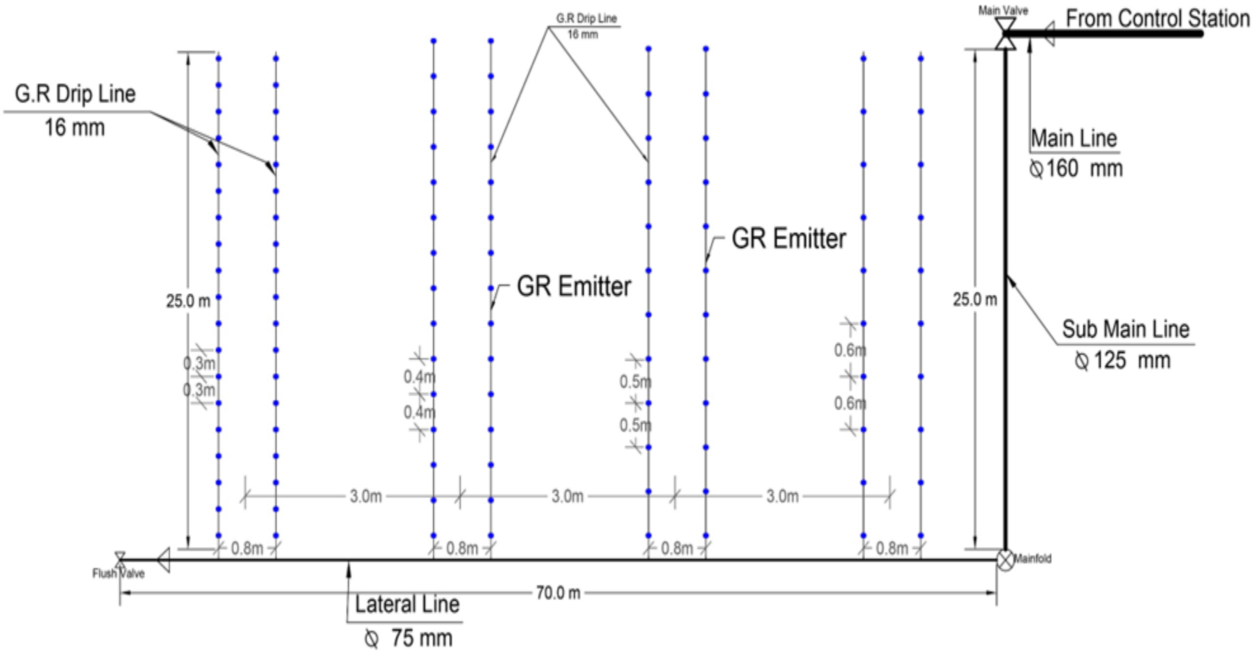

Fig 3. The drip irrigation network

Table 5. The values of the crop coefficient (KC) for mango (Allen et al 1998)

KC stage	KC_{ini}	KC_{mid}	KC_{end}	KC_{ah}	KC_{dor}
Value	0.5	0.7	0.6	0.6	0.05

2.4.3 The total irrigation requirements

The total irrigation requirements for mango trees were computed using the following equation as suggested by Allen et al (1998):

$$\mathrm{IR} = \mathrm{ETc} \times \left(\frac{1}{1-\mathrm{LR}}\right) / \mathrm{Ea} \text{ .... (3)}$$

Where IR represents irrigation requirements (mm/day), ETc represents crop evapotranspiration (mm/day), LR represents leaching requirements (%), and Ea represents application efficiency (%).

2.5 Drip irrigation system evaluation

2.5.1 Uniformity of the design distribution

The uniformity of the design distribution was determined using the following equation as outlined by James (1988):

$$\mathrm{EU} = 100\left(1.0 - 1.27\frac{\mathrm{CV}}{\sqrt{\mathrm{N_p}}}\right)\frac{\mathrm{q_n}}{\mathrm{q_a}} \text{ .... (4)}$$

Where EU represents design uniformity of distribution (%), CV represents manufacturing coefficient of variation for the emitter, N_p represents number of emitters per plant, q_n represents minimum emitter discharge (l/h), and q_a represents average discharge required (l/h).

2.5.2 Field distribution uniformity

The field distribution uniformity was computed using the following equation as prescribed by Merriam and Keller (1978):

$$\mathrm{FDU} = (\mathrm{q_n}/\mathrm{q_a}) \times 100 \text{ .... (5)}$$

Where FDU represents field distribution uniformity (%), q_n represents the average of the lowest quarter (1/4) emitter flows (l/h), and q_a represents the average of all emitters flow (l/h).

2.6 Plant indicators

The fruit yield at harvest was determined by weighing all the fruits from each tree, offering a direct assessment of the impact of irrigation treatments on fruit production.

2.7 Water use efficiency

The water use efficiency for each treatment was computed by dividing the average total product of each treatment by the total water applied during one season for that treatment, as per the equation outlined by Doorenbos and Kassam (1979):

$$WUE = Y/IR \text{ .... (6)}$$

Where WUE represents water use efficiency (Kg/m^3), Y represents yield for each treatment (Kg), and IR represents irrigation requirements throughout the season per treatment (m^3).

2.8 Experimental design

The experiment spanned two agricultural seasons (2022 and 2023), running from January 1, 2022, to December 31, 2023, employing a completely randomized design to investigate the influence of varying irrigation water quantities on mango tree growth and yield. The experiment examined four levels of irrigation requirements (IR) at 50%, 60%, 75%, and 100%, using four different dripper spacing distances (60, 50, 40, and 30 cm). The irrigation levels of 50%, 60%, 75%, and 100% were chosen to represent a gradient of water availability, from severe deficit to full irrigation, allowing for the assessment of water use efficiency and crop productivity across a range of water application scenarios. The irrigation water amounts for each treatment were specified in the experimental design, which included 12 trees from a mango orchard of uniform size, age, and shape. These trees were divided into four treatments, with each treatment comprising three trees. Each tree served as an individual replicate, acting as a self-contained experimental unit. The trees were irrigated using two lines of drip hoses on either side, with different distances between the drippers as delineated in the experimental setup. Replicates were allocated as depicted in **Fig 4**. The irrigation water amount was regulated by adjusting the spacing between the drippers. Uniform drippers of the same type were utilized across all drip lines in the experiment, maintaining consistent operating pressure for all replicates within the same treatment throughout the growing season.

2.9 Drip irrigation system evaluation

The evaluation results of the irrigation system characteristics presented in **Table 6** indicate its excellent performance, operating with optimal efficiency, and undergoing continuous monitoring throughout the trial

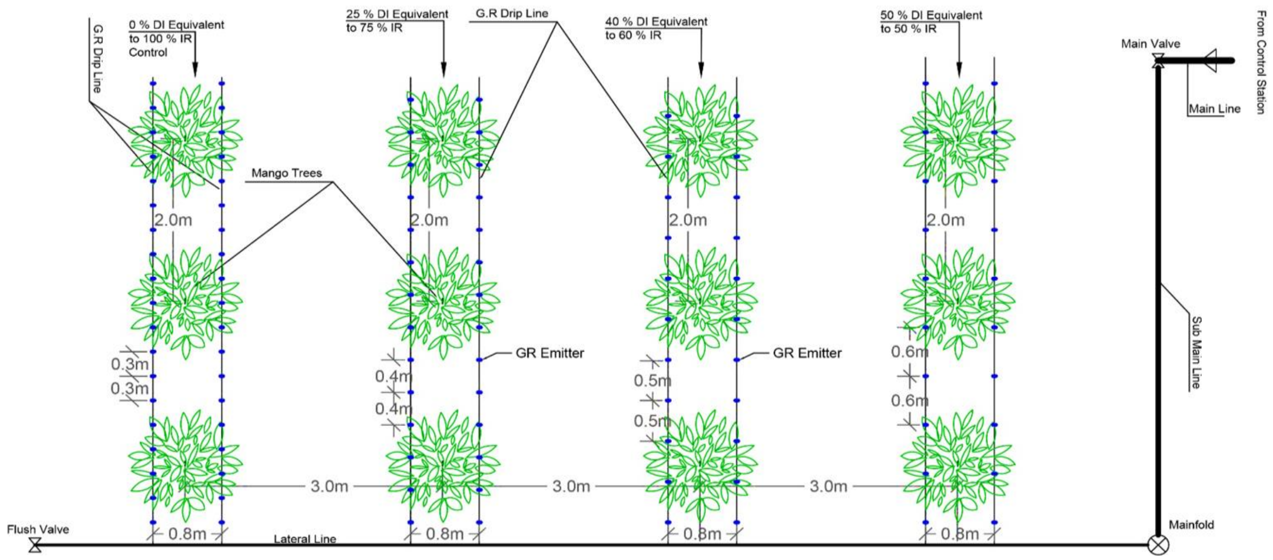

Fig 4. The experimental design

Table 6. The irrigation system evaluation (Savva and Frenken 2002)

Hydraulic Parameters	Value	Classification
EU (%)	96.24	Excellent
FDU (%)	96	Excellent

season according to Savva and Frenken (2002). It effectively delivers the irrigation requirements with the estimated and fixed design quantity necessary for mango trees according to each experimental treatment. Moreover, the emitter used has demonstrated ideal distribution and uniformity of irrigation water at the required operating pressure in the field. Consequently, this system supports the precise management practices employed for each treatment, exhibiting high efficiency in water and energy usage. These findings align with the evaluations of drip irrigation systems conducted by Sadatiya et al (2019) and Abdulhadi and Alwan (2020).

2.10 Statistical analysis

Statistical analysis was conducted using a completely randomized block design, where all data were analyzed with three replicates according to Snedecor and Cochran (1980). Means were separated using the Duncan multiple Range test ($P \leq 0.05$) utilizing the (Mstat-C) software package.

3 Results and Discussion

3.1 Irrigation requirements

The outcomes of our scientific inquiry underscore the pivotal role of irrigation requirements and their influence on crop development. **Fig 5** succinctly outlines the total irrigation needs for each treatment over the two seasons (2022 and 2023) and elucidates the diverse irrigation requirements implemented in the pilot experiment. Notably, treatments receiving varying percentages of the total irrigation needs exhibited differing water requirements per Fedden. **Fig 5** offers a comprehensive depiction of irrigation demands, capturing the dynamic fluctuations in water needs throughout the annual crop cycle across the two consecutive seasons (2022 and 2023). Our investigation entailed a meticulous examination of irrigation water requirements during each growth period, furnishing valuable insights into annual water utilization across distinct treatments in predetermined quantities, meticulously structured and managed.

In this context, we found that some local farms irrigate fedden of mango “KEITT” without irrigation management at about 9,000 m^3 annually, according to local field experiments in the study region. While Shaban et al (2020) documented values of 5213.50, 4429.00 and 3648.50 m^3 for 100%, 85%, and 70% of the irrigation requirements of the 'KEITT' mango orchard, respectively. Meanwhile, according to the "Annual Bulletin of Water Resources and Irrigation Statistics" for the

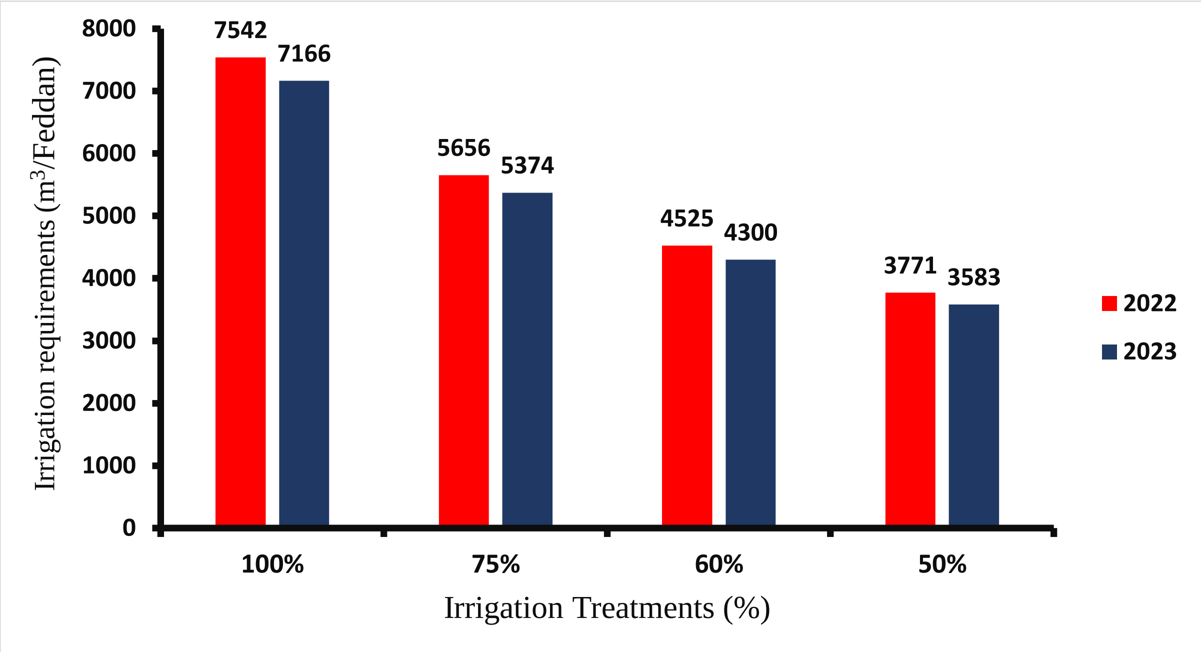

Fig 5. The irrigation requirements for each treatment during the two seasons

year 2023 issued by the Central Agency for Public Mobilization and Statistics in the Arab Republic of Egypt, the actual irrigation rate for mango tree fields is estimated at 6614 m^3 per Fedden annually. In contrast, the average values from our research in this study indicated the following irrigation requirements: 7354, 5515, 4412.5 and 3677 m^3 for the 100, 75, 60 and 50 % treatments, respectively.

3.2 Mango fruit productivity

The findings presented in **Table 7** illustrate fruit productivity indicators across various irrigation treatments throughout the two consecutive growing seasons. It's noteworthy that there were no statistically significant differences in average productivity between the two seasons for the measured parameters across each of the irrigation treatments. The observed differences appear minimal, suggesting that variations in irrigation requirements had an insignificant impact on these indicators. Upon thorough examination, it becomes apparent that the statistical differences favor the treatment applying 50% of irrigation requirements. Collectively, these results suggest that, in our study, the different irrigation levels had little influence on fruiting parameters, underscoring the mango crop's adaptability to diverse irrigation techniques. These findings align closely with those of Zuazo et al (2011).

Table 7. Mango crop productivity for different irrigation treatments during the two seasons

Irrigation treatment	Yield (kg/tree)	
	2022	2023
100% IR	24.330 a	24.380 a
75% IR	25.740 a	25.250 a
60% IR	24.100 a	24.760 a
50% IR	26.060 a	25.940 a

3.3 Water use efficiency

Fig 6 illustrates a compelling trend in water use efficiency, demonstrating an inverse correlation between the kilograms of crop produced per cubic meter of irrigation water and the reduction in irrigation water quantity. This inverse relationship validates that water use efficiency increases as irrigation water decreases, with no statistically significant differences observed in production indicators among the various irrigation treatments.

It is notable that there exists a significant disparity in water use efficiency among the various irrigation treatments. Across the two seasons (2022 and 2023), the treatments (100, 75, 60 and 50%) yielded the following results in terms of water use efficiency: (2.260 & 2.380, 3.190 & 3.290, 3.730 & 4.030 and 4.900 & 5.070 Kg/m^3), respectively. Unexpectedly, the 75% IR

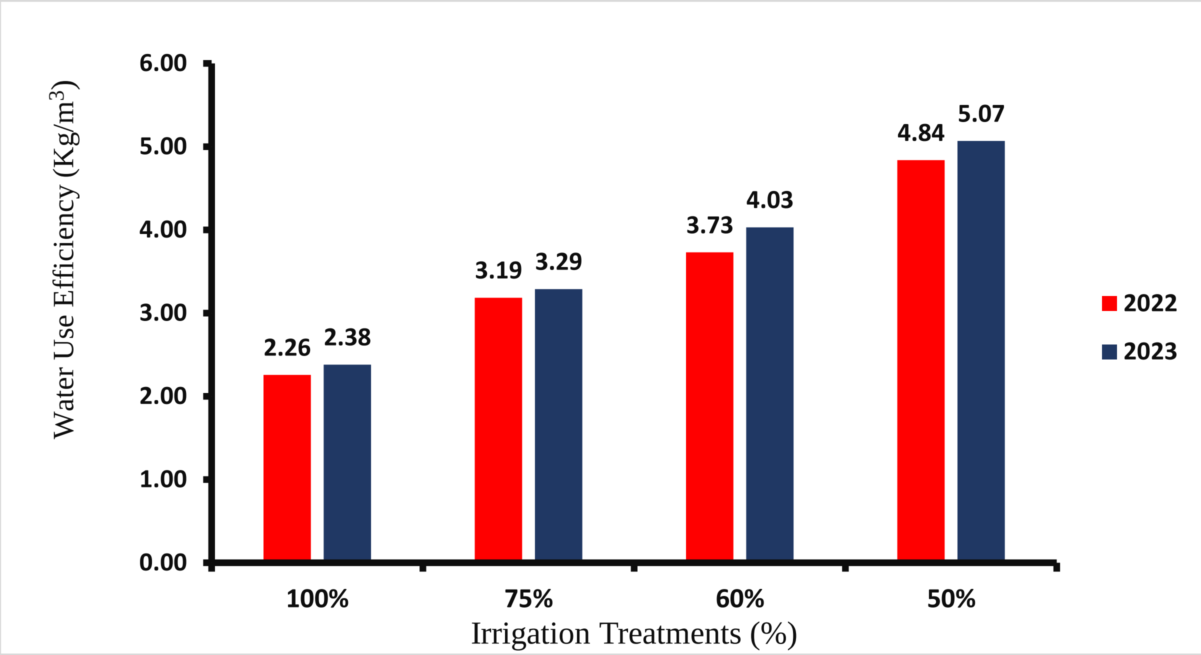

Fig 6. Water use efficiency for different irrigation treatments for the two seasons

treatment did not significantly outperform the 100% IR treatment in terms of water use efficiency. This may be attributed to the inherent drought tolerance of mango trees and their ability to adapt to lower water availability, as suggested by Spreer et al (2009). Particularly noteworthy is the consistently high water use efficiency observed in the 50% irrigation treatment across each consecutive season. These findings align with the principles of sustainable controlled deficit irrigation techniques and underscore the importance of water conservation strategies in agriculture.

An important finding to highlight is the superiority of the 50% irrigation treatment, not only in terms of water use efficiency but also in mango fruit production. This aligns with a strategic water conservation approach, which has successfully reduced irrigation water requirements by 50% without compromising mango yields. These results are consistent with research findings by Zuazo et al (2021), which suggest that sustainable deficit irrigation practices can achieve significant water savings without adversely affecting productivity. While the 50% IR treatment showed high water use efficiency, the long-term effects on soil health and tree longevity should be considered. Prolonged water deficits may lead to soil nutrient depletion and reduced tree vigor, necessitating further studies to optimize irrigation schedules.

4 Conclusions

Based on the findings derived from our research, it is evident that employing systematic deficit irrigation techniques in arid and Semi-Arid regions proves effective and significant in addressing water scarcity. Notably, as indicated by our earlier results, irrigating mango trees at varying levels below full irrigation requirements, such as 50% of the total, did not substantially impact mango growth and productivity.

Such a practice not only enhances water use efficiency but also contributes to water conservation by up to 50%. Our findings suggest that implementing SDI at 50% IR can significantly conserve water without reducing mango productivity. Policymakers and agricultural advisors should consider promoting this technique in water-scarce, semi-arid regions to enhance sustainable agricultural practices. Future research should investigate the application of SDI techniques to different crops and over longer periods to assess their long-term impacts on soil health, crop yield, and water use efficiency.

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