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# Effects of Deficit Irrigation on Growth, Yield, and Quality of Pomegranate (*Punica granatum*) Grown in Semi-Arid Conditions

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**Abstract:** Water scarcity, especially in countries like Egypt, is one of the biggest challenges facing agricultural development. Pomegranate (*Punica granatum*) is drought-resistant but only if the irrigation can be optimized. This can be a crucial approach toward the country's agricultural development. The impact of deficit irrigation on pomegranate growth, yield, and overall fruit quality was observed during this study, which focused on two consecutive years from 2023 to 2024 at a private farm located in El Khatatba, Egypt. It was determined that deficit irrigation of pomegranate was able to achieve a high level of water productivity whilst also achieving a reasonable yield. Trees receiving moderate deficit irrigation had a yield decrease of 10% in comparison to full irrigation; however, this yield decrease did not have a huge overall impact because the level of water saved during the process made up for the reduced yield. Moreover, fruit soluble solids content (SSC) was high when trees received moderate deficit irrigation. Trees that were given severe deficit irrigation had the lowest fruit yields with less juice content, which limits targeted uses like the juice market. Still, these trees produced the highest SSC indicating that sugar becomes concentrated in the fruit when plants are water-stressed. In general, the most efficient treatment was moderate deficit irrigation as it balanced the yield and quality parameters with less water. The resulting data provide assurance that moderate deficit irrigation can be effectively and suitably implemented for pomegranate production in arid regions where water conservation and market quality standards must be satisfied in order to be economically viable. There is also a need to examine the longer-term effects of DI on economic sustainability, plant physiology, and soil biomes.

**Keywords:** pomegranate; deficit irrigation; fruit; water use efficiency

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## 1. Introduction

Water is the most important resource when it comes to agriculture. However, in arid and semi-arid regions, fresh water resources are notably scarce. This consequently leads to compromise in agricultural productivity. A case in point is Egypt, which ranks among the most water-stressed countries with agriculture consuming 85% of the freshwater available [1]. The ever-growing population dynamic, migration to cities and factory establishment combined have put a strain on water resources which were already limited [2]. Therefore, there is need to secure water resources while still ensuring agricultural growth.

Farming in regions that can be termed as dry face harsh conditions, including low rainfall, extremely high evapotranspiration and soil types that simply cannot hold water [3]. A strategy that has been employed includes full irrigation (FI) where the goal is to fully meet the crops water requirement. However, this strategy has led to overuse of water, a counterproductive outcome in resource scarce environments. Over-irrigation not only wastes water but actively contributes to the depletion of freshwater resources, soil salinization and waterlogging. Therefore, the demand for more efficient water management strategies that can provide irrigation without significantly affecting the crop quality or total output has been steadily on the rise.

Deficit irrigation (DI) has been described as a new concept in agricultural water management. This practice is known to create mild stresses in water use which effectively promote plant adaptations aimed at making good use of water [4–6]. Many crops under DI can still retain yield but specification in terms of quality, flavor, sweetness and nutrient concentration could even be improved when high value horticultural crops are used [7–9]. It therefore follows that the use of DI may help resolve the problem of limited water supply and facilitate sustainability in agricultural production.

Pomegranate (*Punica granatum* L.), an ancient fruit with unique cultural and economic importance in many regions of the world, especially in semi-arid and arid regions, can survive severe droughts [10]. Pomegranate trees are deep rooting with good water absorption systems and are able to adapt to long periods of limited water availability without significant loss of productivity [11].

In recent years, the economic importance of pomegranate has surged, driven by growing global demand for fresh fruit, juice, and processed products. Pomegranates are valued for their nutritional content, particularly high levels of antioxidants, vitamins, and minerals, which have earned them the designation of a "superfood" [12]. Key quality attributes such as the fruit soluble solids content (SSC), titratable acidity (TA), juice yield, and fruit size are critical determinants of market value and consumer preference [13].

Many researchers have claimed that DI could improve the quality of pomegranate fruit and at the same time save water use [13–15]. They noted that the elimination of water during periods of stress slightly increased fruit quality attributes like the SSC and TSS, making the fruit sweeter and more desirable to buy [14]. However, extreme water stress can lower the yield, juice content among other quality parameters, all of which are critical for the processing industry. Thus, there is the need to determine the ideal DI conditions to optimize fruit yield and quality while saving on the amount of water used.

Studies on DI within horticultural crops have shown its ability to improve water use efficiency and crop quality in the arid zones [6,7,15–17]. Other research has reported that stress-induced DI can enhance the taste and nutrient components of a plant without lowering the yield in olive and grape crops, which are tolerant to drought [16,18]. The same results have been observed with pomegranates where moderate deficit irrigation (MDI) has been associated with fruit SSC improvement [15]. Although the advantages of DI are well recognized, the effects of SDI are yet to be defined with clarity. According to Gomez-Bellot et al., [18] the DI strategy should be determined for each cultivar as well as local environmental conditions. Higher degrees of water stress are expected to lead to greater water use efficiencies, but generally also cause more fruit yield losses [19]. Additionally, the long-term impacts of DI on plant physiology, soil health, and economic viability remain insufficiently explored, warranting further investigation to refine guidelines for its adoption.

The use of DI for pomegranate production can be very beneficial for the water resource situation in many arid countries like Egypt. However, there are some hurdles that must be crossed, including determining the irrigation schedules that are best suited in terms of the cost-benefit analysis on water savings, yield, as well as fruit quality. Although the previously cited studies have been very helpful in providing insight on the influence of DI on pomegranate, the effects of Egypt's environment and agricultural practices have not yet been examined. The present research seeks to fill this void by analyzing the effects of FI, MDI, and severe deficit irrigation (SDI) on the growth, yield, and fruit quality of pomegranate in an arid area. The specific research objectives are: (1) to estimate the effects of DI on vegetative growth parameters, yield components, and key fruit quality attributes; (2) to determine the water use efficiency (WUE) of pomegranate under different irrigation regimes; and (3) to evaluate the gross sales, irrigation expenditures, and profit for all irrigation regimes.

It was hypothesized that using deficit irrigation strategically during key phenological stages of pomegranate development would not affect the yield of the fruit but would enhance key fruit quality traits such as SSC and TA. In order to test the hypothesis, we undertook a field experiment employing three irrigation treatments: full irrigation, application of a moderate water deficit; and application of an extreme water deficit. Work was undertaken to investigate the influence that different watering regimes have on pomegranate yield and fruit quality. By addressing these objectives, this study aimed to provide practical recommendations for pomegranate growers in arid regions, contributing to the development of sustainable irrigation practices that balance productivity, quality, and resource conservation.

## 2. Materials and Methods

### 2.1. Study Area Description

This study was conducted at a privately owned farm is located in the El-Khatatba region of Egypt 30°36′ N, 30°90′ E. This area lies in the western desert and has a hyper arid climate with very little rainfall, very high temperatures and only sandy soils. This is common in arid regions of agriculture where irrigation is required to procure crops [20].

Soil was found to be composed of 85% sand, 10% silt and 5 % clay particles. Moreover, it was found that the soil organic matter was less than 0.5% and a pH level of 7.8 which indicated a minor order to the alkaline side (Table 1). El-Khatatba, due to its sandy soil low water-holding capacity, necessitates frequent and efficient irrigation to mitigate moisture stress. The electrical conductivity (EC) of the soil was 1.2 dS $m^{-1}$, which is within the tolerance range for pomegranate cultivation [21].

**Table 1.** Study area soil chemical analysis in the El-Khatatba region, Egypt.

| Parameter | Unit | Value |
|---|---|---|
| pH | - | 7.8 |
| Organic matter | % | 0.5 |
| Electrical conductivity (EC) | dS/m | 1.2 |
| Nitrogen (N) | ppm | 35 |
| Phosphorus (P) | ppm | 20 |
| Potassium (K) | ppm | 150 |
| Zinc (Zn) | ppm | 2.5 |
| Iron (Fe) | ppm | 5.0 |
| Soil texture | - | Sandy |

Irrigation water was sourced from a deep groundwater well with an EC of 1.5 dS $m^{-1}$, which is considered suitable for horticultural crops [22] (Table 2). Groundwater salinity levels were monitored monthly to ensure water quality remained within acceptable limits.

The irrigation system employed a modern drip network, with emitters that provided 4L $h^{-1}$ and were designed to minimize evaporation and percolation losses [23].

**Table 2.** Irrigation water chemical analysis in the El-Khatatba region, Egypt.

| Parameter | Unit | Value |
|---|---|---|
| pH | - | 7.5 |
| Electrical conductivity (EC) | dS/m | 1.5 |
| Total dissolved solids (TDS) | mg/L | 960 |
| Sodium ($Na^+$) | mg/L | 180 |
| Potassium ($K^+$) | mg/L | 12 |
| Calcium ($Ca^{2+}$) | mg/L | 80 |
| Magnesium ($Mg^{2+}$) | mg/L | 40 |
| Chloride ($Cl^-$) | mg/L | 300 |
| Sulfate (${SO_4}^{2-}$) | mg/L | 200 |
| Bicarbonate (${HCO_3}^-$) | mg/L | 150 |

Climatic conditions at the farm were monitored using an on-site weather station that recorded temperature, relative humidity, solar radiation, and rainfall (Table 3). During the growing seasons (March–October), the average temperatures were 28 °C in 2023 and 29 °C in 2024, with summer peak temperature reaching 40 °C. Relative humidity ranged between 20% and 60%, and the solar radiation averaged 6.5 kWh $m^{-2}$ $day^{-1}$, consistent with optimal conditions for pomegranate photosynthesis [24]. These climatic data were essential for calculating crop water requirements and optimizing irrigation scheduling [21].

**Table 3.** Study area climatic data in the El-Khatatba region, Egypt, averaged over two years (2023 and 2024). Egyptian Meteorological Authority (EMA) (2024) [25].

| Month | Average Temperature (°C) | Relative Humidity (%) | Solar Radiation (kW h $m^{-2}$ $day^{-1}$) | Rainfall (mm) |
|---|---|---|---|---|
| March | 22 | 50 | 6.2 | 2 |
| April | 25 | 45 | 6.8 | 1 |
| May | 30 | 40 | 7.2 | 0 |
| June | 34 | 35 | 7.6 | 0 |
| July | 36 | 30 | 7.8 | 0 |
| August | 35 | 32 | 7.5 | 0 |
| September | 31 | 40 | 6.9 | 1 |
| October | 28 | 45 | 6.4 | 2 |

### 2.2. Experimental Design

The experiment utilized a randomized complete block design with three irrigation treatments: full irrigation (FI)—100% of crop evapotranspiration (ETc), serving as the control, moderate deficit irrigation (MDI)—75% of ETc, representing mild water stress, and severe deficit irrigation (SDI)—50% of ETc, representing severe water stress. Irrigation treatments were applied to six-year-old ”Wonderful” pomegranate trees that were selected based on their similar approximated strength and dimensions (Figure 1). Deficit irrigation was achieved by reducing the irrigation duration (hours per irrigation event) while maintaining the same number of emitters per tree. Each year, treatments were replicated three times, with 10 trees per replicate. Uniform cultural practices, including pruning, pest control, and fertilization, were applied across all plots to minimize variability [10,26]. The trees were spaced at 4 m, both within rows and between rows, which ensured adequate canopy development and air circulation.

**Figure 1.** The flowering and fruit development of six-year-old "Wonderful" pomegranate trees located in the El-Khatatba region, Egypt.

### *2.3. Irrigation Scheduling and Management*

Irrigation was scheduled based on crop evapotranspiration (ETc), calculated using the FAO Penman–Monteith equation [19]:

$$\mathrm{ETc} = \mathrm{ET}_0 \times \mathrm{Kc} \tag{1}$$

where $\mathrm{ET}_0$ is the reference evapotranspiration derived from weather data; and Kc is the crop coefficient for pomegranate during the different phenological stages—vegetative growth (March–April): 0.7, flowering and fruit setting (May–June): 0.9, fruit development (July–August): 1.0, and maturity/harvest (September–October): 0.8.

Sensors were installed to a depth of 20 cm in all three treatments so that soil moisture values could be measured and these sensors aided with real-time management of irrigation, thus preventing over- or under-irrigation [25]. The reported measures of daily water application volumes were used to determine whether irrigation systems were efficient and whether the required treatment designs were adhered to.

### *2.4. Fertilization and Soil Management*

Given the low fertility of the sandy soils, macronutrients were supplied through fertigation. Nitrogen was applied as urea at a rate of 250 kg $\mathrm{ha}^{-1}$ annually to support both vegetative and reproductive growth [14]. Phosphorus was delivered as monoammonium phosphate at 150 kg $\mathrm{ha}^{-1}$ annually to promote root development and fruit setting. Potassium was applied as potassium sulfate at 200 kg $\mathrm{ha}^{-1}$ annually, essential for fruit quality and stress tolerance [13].

Micronutrients, including zinc and boron, were applied as a foliar spray during critical growth stages to prevent deficiencies [12]. Soil amendments such as gypsum were added to enhance soil structure and improve water infiltration. Plant/animal compost was incorporated at 5 kg of compost $\mathrm{tree}^{-1}$ prior to the experiment during dormancy to increase soil organic matter and improve nutrient-retention capacity [22].

### *2.5. Data Collection*

Growth parameters, including the tree height, canopy diameter, and trunk diameter, were measured at the end of each growing season. Tree height was recorded using a telescopic measuring pole; canopy diameter was determined by averaging two perpendicular measurements; and trunk diameter was measured at 20 cm above the soil surface using a digital caliper [23]. Yield components, including total fruit yield tree$^{-1}$, number of fruits tree$^{-1}$, and average fruit weight were recorded at harvest. Fruit quality was evaluated by measuring the fruit soluble solids content (SSC) with a digital refractometer, expressed as a percentage [26]. Titratable acidity (TA) was determined via titration with 0.1 N NaOH, expressed as a percentage of citric acid equivalent. Juice content was calculated as the ratio of juice weight to total fruit weight, expressed as a percentage. The WUE was calculated as the ratio of fruit yield (kg) to total water applied (m$^3$), providing a key metric for evaluating irrigation efficiency under each treatment [4].

### *2.6. Statistical Analysis*

Data were analyzed using SPSS Statistics (ver. 25, IBM, Armonk, NY, USA). Initially, numerical normality and homogeneity of variance were assessed using Shapiro–Wilk's and Levene's tests, respectively. Subsequently, analysis of variance (ANOVA) was conducted to detect significant differences among treatments for all parameters. Preliminary analysis indicated no significant differences between seasons for all parameters; therefore, data from both seasons were pooled, and a combined analysis was performed to assess the treatment effects comprehensively. When appropriate, post hoc comparisons were performed using the least significant difference (LSD) test at a 5% significance level.

## 3. Results

### *3.1. Growth Parameters*

Irrigation treatments differed across both growing seasons and significantly impacted tree height, canopy diameter, and trunk diameter (Figure 2). Trees that were subjected to FI exhibited the largest dimensions consistently. The trees under MDI exhibited slightly reduced growth but the parameters remained reduced in comparison to FI trees. On the other hand, trees under SDI had the most significant reduction in tree height, canopy diameter, and trunk diameter compared to FI trees.

### *3.2. Yield Components*

Irrigation treatments significantly influenced yield parameters such as tree fruit counts, total yield, and average fruit weight (Figure 3). The highest total yield and number of fruits was observed among the FI treated trees. The total yield derived from MDI trees was about 90% of that of FI trees, and there were only minor decreases in the number and weight of fruits. On the other hand, SDI induced a decrease of 32% and 25% of the total yield in comparison to FI and MDI trees, respectively. The number of fruits was also reduced by 23% and 18% under the SDI environment compared to that of FI and MDI trees, respectively.

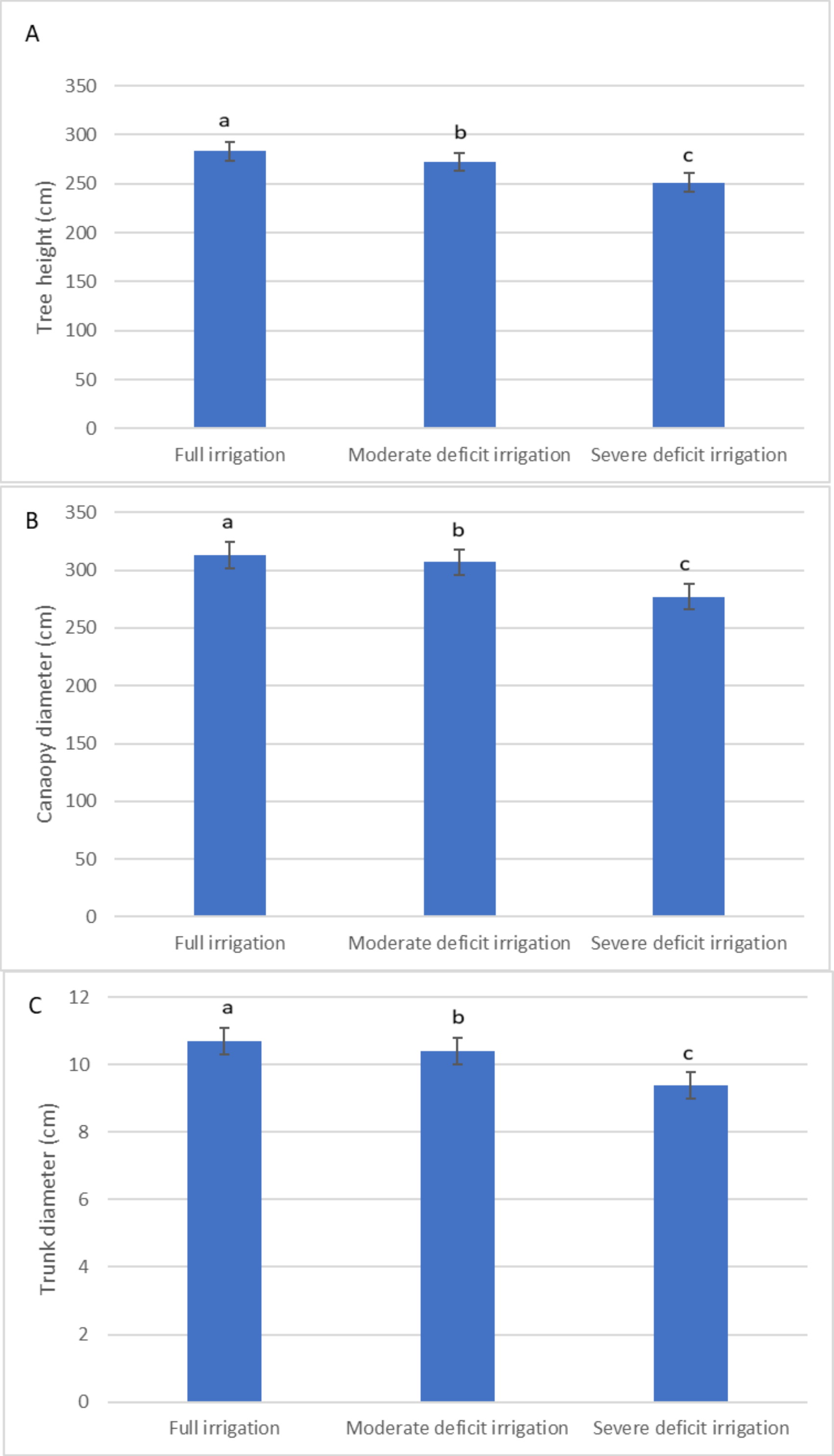

**Figure 2.** Growth parameters ((**A**) tree height, (**B**) canopy diameter, and (**C**) trunk diameter) of pomegranate trees receiving full irrigation, moderate deficit irrigation, and severe deficit irrigation averaged over two years (2023 and 2024) in the El-Khatatba region, Egypt. Error bars are ± SE. Different letters indicate significant differences at $p \leq 0.05$.

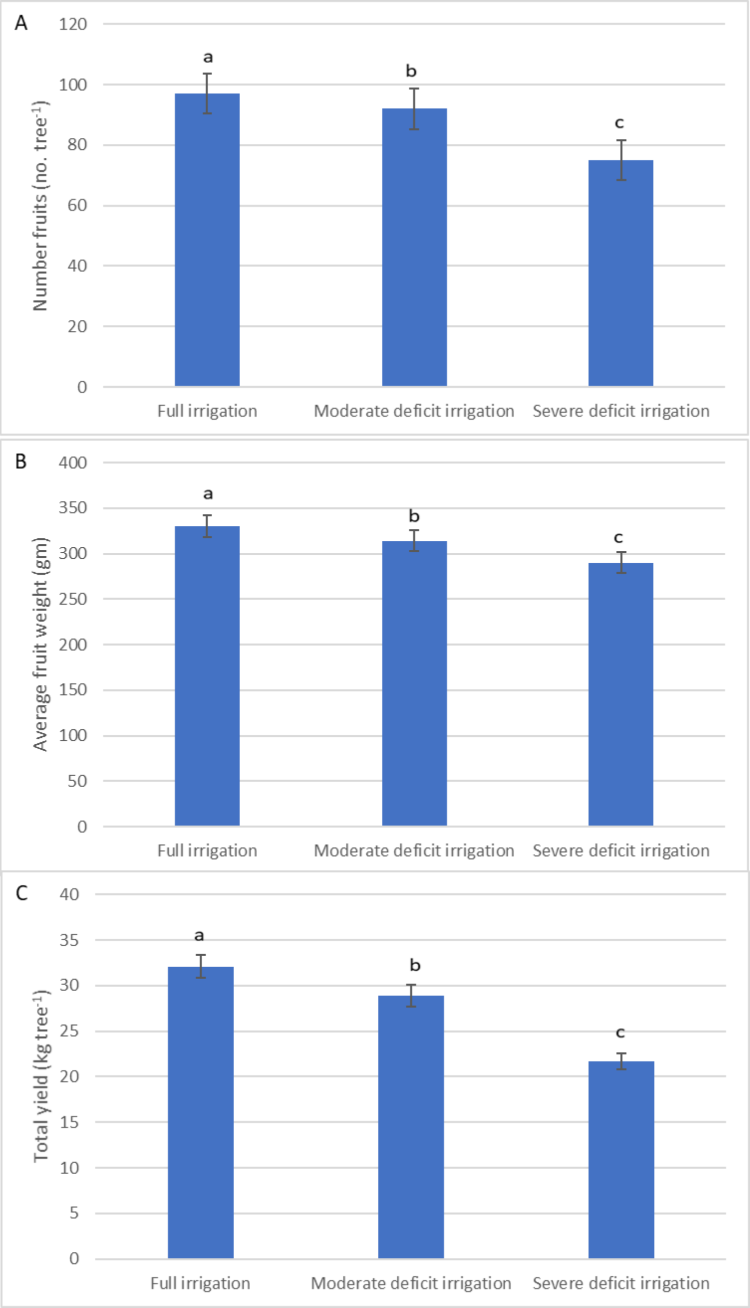

**Figure 3.** Yield components ((**A**) number of fruits, (**B**) average fruit weight, and (**C**) total yield) of pomegranate trees receiving full irrigation, moderate deficit irrigation, and severe deficit irrigation averaged over two years (2023 and 2024) in the El-Khatatba region, Egypt. Error bars are ± SE. Different letters indicate significant differences at $p \leq 0.05$.

### 3.3. Fruit Quality Parameters

Fruits SSC, TA, and juice percentage were greatly influenced by the irrigation treatment (Figure 4). Fruit SSC for trees under SDI had the highest value and was much higher compared to fruit SSC from FI or MDI trees. In contrast, FI trees bore the lowest fruit SSC value. Trees irrigated with SDI had the lowest juice content value and as such, had lower profitability for the juice production market. The fruit TA remained constant amid different irrigation treatments suggesting that fruit acidity levels were more tolerant to irrigation fluctuation.

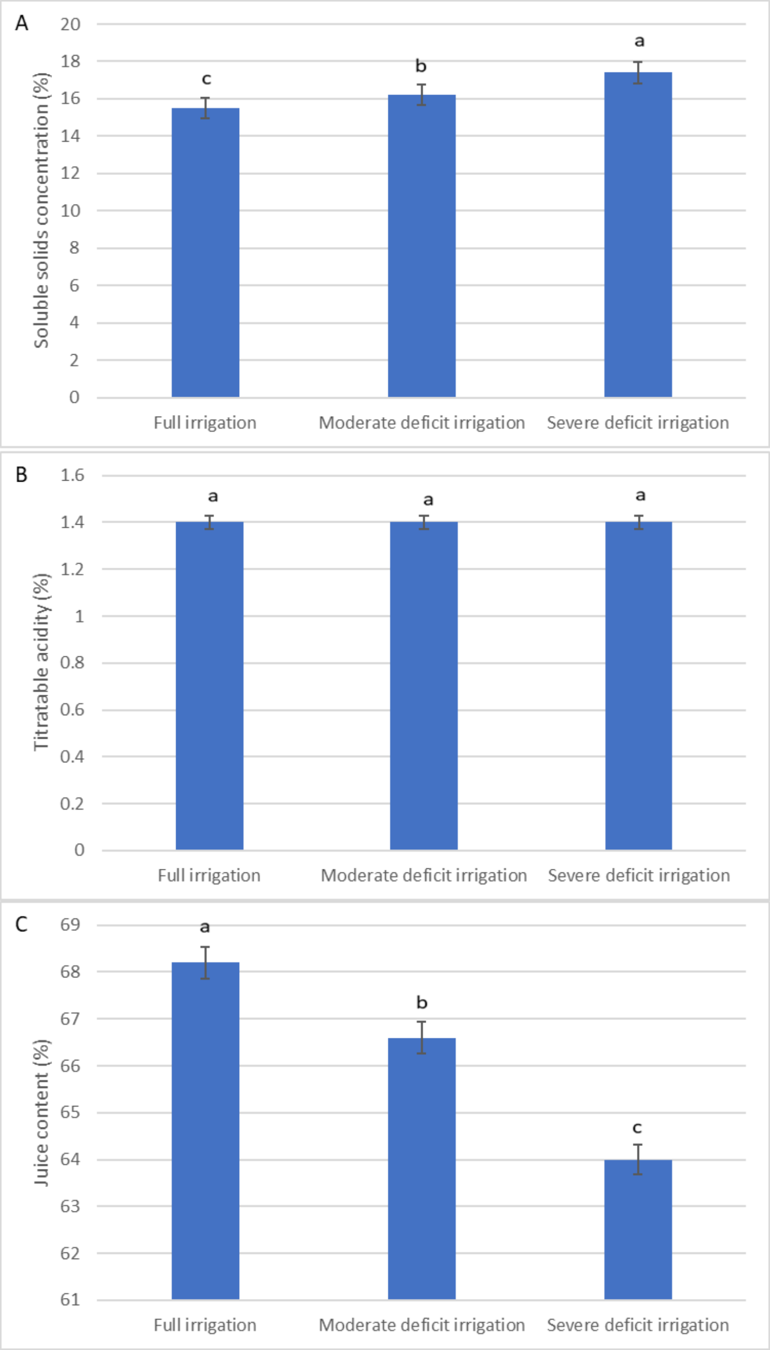

**Figure 4.** Fruit quality parameters ((**A**) soluble solids content, (**B**) titratable acidity, and (**C**) juice content) of pomegranate trees receiving full irrigation, moderate deficit irrigation, and severe deficit irrigation averaged over two years (2023 and 2024) in the El-Khatatba region, Egypt. Error bars are ± SE. Different letters indicate significant differences at $p \leq 0.05$.

### *3.4. Water Use Efficiency (WUE)*

For each growth season, the trees were provided with differing amounts of water, depending on the irrigation treatment. Trees under the FI system received 15 $m^3$ $tree^{-1}$, while for the MDI system, 11.3 $m^3$ $tree^{-1}$ was supplied, and for the SDI system, 7.5 $m^3$ $tree^{-1}$ was supplied. The WUE efficiency increased 20% for MDI trees compared FI trees and increased to 35% for SDI trees compared to FI trees (Figure 5). Furthermore, the water use efficiency WUE was highest for trees that utilized SDI due to the 50% decrease in water usage and 32% yield decrease in comparison to FI trees.

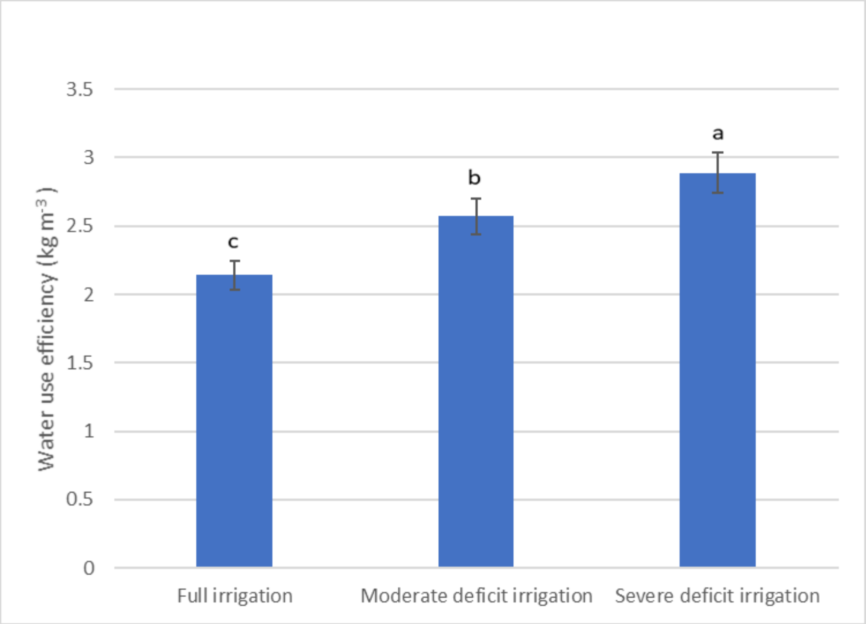

**Figure 5.** Water use efficiency for pomegranate trees receiving full irrigation, moderate deficit irrigation, and severe deficit irrigation averaged over two years (2023 and 2024) in the El-Khatatba region, Egypt. Error bars are ± SE. Different letters indicate significant differences at $p \leq 0.05$.

### 3.5. Water Economics and Productivity

Table 4 shows the income, cost of irrigation, net profits, and water productivity as the result of each irrigation treatment measured by fruit yield and cost of irrigation. Such irrigation strategies, along with their corresponding parameter differences, help to explain how efficiently the irrigation methods performed in terms of the resource and economic efficiency of pomegranate cultivation in an arid environment.

**Table 4.** The economic analysis and water productivity for pomegranate trees receiving full irrigation (FI), moderate deficit irrigation (MDI), and severe deficit irrigation (SDI) averaged over years (2023 and 2024) in the El-Khatatba region, Egypt.

| Treatment | Total Yield (kg tree$^{-1}$) | Income (EG tree$^{-1}$) | Irrig. Cost (EGP tree$^{-1}$) | Net Profit (EGP tree$^{-1}$) | Water Productivity (EGP m$^{-3}$) |
|---|---|---|---|---|---|
| **FI** | 32.1 | 4800 | 1000 | 3800 | 253.3 |
| **MDI** | 28.9 | 4335 | 750 | 3585 | 318.7 |
| **SDI** | 21.7 | 3255 | 500 | 2755 | 367.3 |

#### 3.5.1. Total Yield and Income

Full irrigation enhanced the trees' total yield to an ample 32.1 kg, leading to unrestricted growth along their optimal fruit development as noted in Table 4. Consequently, earning over 4800 EGP for each tree which translated to 96 dollars. Nevertheless, while applying FI and ignoring the resource use cost of water, the previously mentioned limit on water input inflates the water productivity rate.

Trees receiving MDI achieved a slightly reduced yield (28.9 kg tree$^{-1}$), only 9.7% less than trees receiving FI, despite using 25% less water. This demonstrated the plant's capacity to adapt to moderate water stress by sustaining fruit development and growth. The income for trees receiving MDI was 4335 EGP tree$^{-1}$ (USD 87 tree$^{-1}$), reflecting its ability to maintain economic returns while conserving water. Trees receiving SDI resulted in a significant yield reduction of 21.7 kg tree$^{-1}$, 32% lower than trees receiving FI. This was due to severe water stress that limited key physiological processes like fruit setting and development.

The income for trees receiving SDI dropped to 3255 EGP tree$^{-1}$ (USD 65 tree$^{-1}$), making it the least economically favorable in terms of yield and revenue generation.

### 3.5.2. Irrigation Costs and Water Use

The irrigation cost for trees receiving FI was the highest at 1000 EGP tree$^{-1}$ (USD 20 tree$^{-1}$), reflecting the large volume of water (15 m$^3$ tree$^{-1}$) applied (Table 4).

Although this approach elevated the yield, it restricted the economic efficiency, particularly in water scarce situations where the cost of inputs is crucial. Trees treated with MDI incurred the irrigation cost of 750 EGP tree$^{-1}$ (USD \$15 tree$^{-1}$) and applied irrigation water of 11.3 m$^3$ tree$^{-1}$. The MDI system expressed a water saving of 25% in relation to FI while greater water use efficiency was achieved jointly with competitive yields. Trees with SDI had the least irrigation cost of 500 EGP tree$^{-1}$ (USD \$10 tree$^{-1}$) due to the lowest water applied at 7.5 m$^3$ tree$^{-1}$. Still, the sharp reduction in yield and income in the case of SDI showed that intensive water saving measures are not appropriate for commercial farming when there is good access to water.

### 3.5.3. Net Profit

Based on Table 4, we can assert that the overall highest yield and income stemmed from trees receiving FI, which recorded a staggering net profit score of 3800 EGP tree$^{-1}$ (USD 76 tree$^{-1}$); however, as more water considerations are added to the equation and higher irrigation expenses occur, the overall economic advantage will be much lower. Trees receiving MDI recorded a net profit of 3585 EGP tree$^{-1}$ (USD 72 tree$^{-1}$), a 5% net profit decrease that resulted from a 10% tree yield decrease and 25% lower water costs in comparison to FI trees. This underlines how cost effectiveness and the generation of revenue can be maintained with restraint use of MDI. In the case of SDI, these trees recorded a net profit of 2755 EGP tree$^{-1}$ (USD 55 tree$^{-1}$), a 28% net profit decrease that resulted from a 32% tree yield decrease and 50% lower water costs in comparison to FI trees.

### 3.5.4. Water Productivity

The trees which were given FI had the least water productivity of 253.3 EGP m$^{-3}$ (USD 5.10 m$^{-3}$), showing the wastefulness of supplying the largest amount of water to maintain the highest yield and income (Table 4). In comparison, MDI method increased the water productivity to 318.7 EGP m$^{-3}$ (USD \$6.40 m$^{-3}$) which was 25.8% higher than FI. This also validates that controlled water application greatly increases economic output per applied water unit without pressure. Moreover, trees provided with SDI exceeded MDI trees in water productivity with 367.3 EGP m$^{-3}$ (USD \$7.30 m$^{-3}$), a 15% increase in water productivity compared to MDI trees. However, the trade-off between water efficiency and reduced profitability limits its applicability in scenarios prioritizing yield and income.

## 4. Discussion

### *4.1. Growth Parameters*

Trees that received FI demonstrated a greater tree height, canopy diameter, and trunk diameter than other trees, displaying how optimal water availability had enhanced their vegetative growth and corroborated the role of water in expanding cells and enhancing the transportation of essential nutrients as well as photosynthetic activity, which are all necessary for optimal vegetative development [24,27–29]. The FI treatment ensured optimal hydration and allowed for unrestricted metabolic processes necessary for growth. Trees receiving MDI exhibited only slight reductions in vegetative growth compared to FI, suggesting that moderate water stress induced physiological adaptations that help maintain growth. These adaptations likely include increases in root-to-shoot ratios, improved water uptake efficiency, and reduced canopy transpiration, enabling trees under MDI to sustain growth while conserving water [29]. However, trees subjected to SDI showed significant reductions in vegetative growth. The observed decreases in tree height, canopy diameter, and trunk diameter are consistent with previous research with young and older pomegranate trees [9,18,30–32], which found that severe water stress restricts carbohydrate production and its allocation to vegetative organs. In contrast, Intrigliolo et al. [33] showed that trees receiving a regulated DI applied early in the season (during the flowering and fruit setting) and then returned to FI had similar growth parameters as trees receiving FI. Trees under SDI conditions prioritized survival over growth by reallocating resources to vital physiological functions such as root activity and stomatal regulation [34]. This reallocation, coupled with a reduced canopy size, likely limited photosynthetic capacity, further compounding growth constraints.

### *4.2. Yield Components*

Total fruit yield, number of fruits per tree, and the average weight of the fruit were greatly impacted by the different irrigation methods. In this case, all trees that received FI had maximum yields, thus paving the way for nearly sufficient or rather abundant water availability for fertile growth to take place. Studies on pomegranate and other drought-resistant crops indicate that sufficient moisture at important growth phases, such as the flowering and fruit setting stages, are necessary for optimal pollination, retention, and fruit development [9,14,16,30–32]. Trees receiving MDI achieved approximately 90% of the total yield of trees under FI, demonstrating pomegranate's resilience to moderate water stress. This suggests that MDI may enhance reproductive efficiency by prioritizing fruit production over vegetative growth [15,31]. In contrast, Intrigliolo et al. [33] and Leal et al. [34] reported an increase in the number of pomegranate fruits under the continuous DI condition, which they attributed to a reduction in the drop of the reproductive organs, even though fruit were smaller. Similarly, Centofanti et al. [35] reported that DI strategies as low as 35% ETc did not significantly affect pomegranate yield, which reinforces the importance of determining the appropriate DI strategy for each cultivar and for local environmental conditions [18]. The reduced competition for resources in MDI-treated trees likely directed more resources to reproductive organs, maintaining or increasing yields for specific cultivars even under reduced water input. Conversely, SDI resulted in substantial reductions in both fruit count and total yield, highlighting the detrimental effects of severe water stress on reproductive processes. The limited water availability under SDI likely disrupted flower development, reduced pollination success, and increased fruit drop, leading to lower yields [9,29,30]. Additionally, the smaller fruit size observed under SDI can be attributed to restricted cell expansion during fruit growth, a growth stage particularly sensitive to water availability [26]. These findings emphasize the trade-offs between water conservation and productivity under severe-water-stress conditions.

### *4.3. Fruit Quality*

Fruit quality attributes, including the SSC, TA, and juice content, exhibited significant variation across irrigation treatments, reflecting the influence of irrigation on fruit composition. Trees receiving MDI or SDI produced fruit with a higher SSC compared to FI, with SDI trees having the highest SSC values. This result was consistent with other pomegranate research [30,33,36–41], where it has been suggested that water stress can increase the conversion of starch to sugar and result in sugars accumulating in fruit due to reduced dilution effects [24,37]. Enhanced SSC is a desirable trait for fresh consumption markets, where sweetness is a key determinant of consumer preference. These findings also align with previous research on pomegranate, grapes, and other fruits, where moderate water stress enhanced flavor by concentrating sugars and organic acids [15,28–37,41], even though the SSC for FI and MDI trees was not significantly different for Tarantino et al. [9] or Nasrabadi et al. [36]. Research has also shown that MDI influenced other fruit quality parameters, resulting in an increase in the fruit phenolic content and antioxidant capacity, which are important for market acceptability and consumer choice [30,32,36,42]. In addition, fruit SSC increased significantly during storage at 5 °C when trees were water-stressed [34,35,37]; however, the higher SSC under SDI must be considered in relation to the reductions in fruit size and juice content, which may limit its suitability for juice-processing markets. Juice content, a critical parameter for processing applications, was reduced by 6% under SDI, likely due to the impact of water stress on cell turgor and juice accumulation, as suggested by Martínez et al. [26]. Fruit from trees under MDI, however, maintained an acceptable juice content while improving the SSC, making it a more versatile option for both fresh consumption and processing markets. Fruit TA remained stable across treatments, which reinforced results by Tarantino et al. [9] and suggested that acidity levels in pomegranate are less sensitive to irrigation variations compared to SSC. This stability in TA may help maintain flavor balance under diverse irrigation conditions, as reported by Holland et al. [12].

### *4.4. Water Use Efficiency (WUE)*

The WUE showed a clear ascending trend from FI to SDI, reflecting increasing water utilization efficiency as irrigation volumes were reduced. This was in agreement with Meshram [32] and Intrigliolo et al. [33], while Tarantino et al. [9] reported no statistical difference for WUE among DI treatments. Trees receiving SDI exhibited the highest WUE due to the substantial reduction in water input relative to yield; however, the associated yield losses under SDI emphasize the trade-offs between prioritizing water conservation and maintaining productivity. These findings were also consistent with studies on drought-tolerant crops including olives and grapes, where severe deficit irrigation maximized WUE but resulted in reduced yield potential [8,16,17,42].

The trees under MDI had the best balance of the irrigation strategy, as they exhibited a significant increase in WUE relative to FI while being able to sustain acceptable yield levels. This means that MDI can achieve water economy in areas where water is limited. The relatively low impacts on yield that are observed with MDI, in conjunction with the better quality of fruit, also make MDI an appropriate irrigation method for growing pomegranates in dry areas.

### *4.5. Implications for Sustainable Agriculture*

The findings of this research contribute meaningfully to the knowledge of pomegranate farmers operating in water-sparse regions. The use of MDI in pomegranate cultivation addresses the exigency of water rationing whilst augmenting the productivity and its quality. It allows the growers to save water without greatly affecting yield or the ability to sell the produce. For the dual market of table and processing pomegranates, the MDI sales are favorable, while SDI would be more appropriate for niche markets that prefer more sweetness even though juice production was reduced. Furthermore, the integration of real-time soil moisture measurements, weather elements, and the crop cycle could optimize water uses and improve flexibility in responding to climate change.

## 5. Conclusions

This research showed that deficit irrigation is a very important management tool for tree growth, fruit yield, fruit quality, and water use efficiency of ”Wonderful” pomegranate trees grown in arid areas of Egypt. This study highlighted the potential of MDI as an effective water-saving irrigation strategy for pomegranate production in arid regions. During MDI, the WUE increase was attributed to water-conserving characteristics without a great reduction in yield. The MDI also resulted in an increase in the fruit chemical quality attribute of SSC. Physiological measurements, such as the tree height, canopy diameter, and trunk diameter, confirmed that the trees were able to respond to boundaries set by water stress through osmotic adjustment and controlled water movements. However, SDI induced a significant crop yield reduction, thus compromising the need to strike a balance between saved water and crop yield. By balancing productivity, quality, and resource conservation, MDI represents a viable solution for addressing the dual challenges of water scarcity and agricultural sustainability. Further research should include the long-term effects of DI on soil and additional tree metrics such as the number of flowers, percent fruit set, as well as the use of precision irrigation applications for better water management.

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## References

1. Allam, M.N.; Allam, G.I. Water resources in Egypt: Future challenges and opportunities. *Water Int.* **2007**, *32*, 205–218. [CrossRef]
2. El-Sadek, A. Water desalination: An imperative measure for water security in Egypt. *Desalination* **2010**, *250*, 876–884. [CrossRef]
3. Qureshi, A.S.; McCornick, P.G.; Sarwar, A.; Sharma, B.R. Challenges and prospects of sustainable groundwater management in the Indus Basin, Pakistan. *Water Resour. Manag.* **2010**, *24*, 1551–1569. [CrossRef]
4. Geerts, S.; Raes, D. Deficit irrigation as an on-farm strategy to maximize crop water productivity in dry areas. *Agric. Water Manag.* **2009**, *96*, 1275–1284. [CrossRef]
5. Fereres, E.; Soriano, M.A. Deficit irrigation for reducing agricultural water use. *J. Exp. Bot.* **2007**, *58*, 147–159. [CrossRef]
6. Elmenofy, H.M.; Hatterman-Valenti, H.M.; Hassan, I.F.; Mahmoud, M.M.A. Effects of Deficit Irrigation and Anti-Stressors on Water Productivity, and Fruit Quality at Harvest and Stored 'Murcott' Mandarin. *Horticulturae* **2023**, *9*, 787. [CrossRef]
7. Chaves, M.M.; Zarrouk, O.; Francisco, R.; Costa, J.M.; Santos, T.; Regalado, A.P.; Rodrigues, M.L.; Lopes, C.M. Grapevine under deficit irrigation: Hints from physiological and molecular data. *Ann. Bot.* **2010**, *105*, 661–676. [CrossRef]
8. Shailendra, A.; Narendra, A. The effect of trickle irrigation on growth yield and quality of pomegranate (*Punica granatum* L.) in cv. Ganesh in Chhattisgarth region. *J. Agric. Sci.* **2005**, *39*, 175–181.
9. Tarantino, A.; Frabboni, L.; Disciglio, G. Water-Yield Relationship and Vegetative Growth of Wonderful Young Pomegranate Trees under Deficit Irrigation Conditions in Southeastern Italy. *Horticulturae* **2021**, *7*, 79. [CrossRef]

10. Melgarejo, P.; Salazar, D.M.; Artés, F. Organic pomegranate production: Effects of irrigation on fruit yield. *HortScience* **2000**, *35*, 423–427.
11. Mirdehghan, S.H.; Rahemi, M. Seasonal changes of mineral nutrients and phenolics in pomegranate. *Sci. Hortic.* **2007**, *111*, 120–127. [CrossRef]
12. Holland, D.; Hatib, K.; Bar-Ya'akov, I. Pomegranate: Botany, horticulture, breeding. *Hortic. Rev.* **2009**, *35*, 127–191. [CrossRef]
13. Martínez, J.J.; Hernández, F.; Melgarejo, P. Improvement of fruit quality in pomegranate through regulated deficit irrigation. *Sci. Hortic.* **2009**, *120*, 100–106. [CrossRef]
14. Patil, S.R.; Thorat, V.A.; Golegaonkar, P.G.; Reddy, P.S. Influence of deficit irrigation on pomegranate yield and quality. *J. Hortic. Sci.* **2014**, *56*, 237–245.
15. Yaghoobi, S.R.; Moghadam, H.A.; Karimi, S. Response of pomegranate fruit quality to deficit irrigation. *J. Agric. Sci. Tech.* **2012**, *14*, 933–944.
16. Hassan, I.F.; Ajaj, R.; Gaballah, M.S.; Ogbaga, C.C.; Kalaji, H.M.; Hatterman-Valenti, H.M.; Alam-Eldein, S.M. Foliar Application of Nano-Silicon Improves the Physiological and Biochemical Characteristics of 'Kalamata' Olive Subjected to Deficit Irrigation in a Semi-Arid Climate. *Plants* **2022**, *11*, 1561. [CrossRef]
17. Intrigliolo, D.S.; Castel, J.R. Response of grapevine cv. 'Tempranillo' to timing and amount of irrigation: Water relations, vine growth, yield and berry and wine composition. *Irrig. Sci.* **2010**, *28*, 113–125. [CrossRef]
18. Gómez-Bellot, J.; Parra, A.; Nortes, P.; Alarcón, J.J.; Ortuño, M.F. Searching for a deficit irrigation strategy to save water and improve fruit quality without compromising pomegranate production. *Sci. Hortic.* **2024**, *324*, 112631. [CrossRef]
19. Marsal, J.; Gelly, M.; Mata, M.; Arbonés, A.; Rufat, J.; Girona, J. Postharvest regulated deficit irrigation in 'Summit' sweet cherry: Effects on vegetative growth and fruit quality. *Agric. Water Mgmt.* **2011**, *98*, 516–522.
20. Hegazy, A.K.; Fahmy, G.M.; Ali, M.I.; Gomaa, N.H. Vegetation diversity in natural and agro-ecosystems of arid lands. *Comm. Ecol.* **2004**, *5*, 163–176. [CrossRef]
21. Allen, R.G.; Pereira, L.S.; Raes, D.; Smith, M. Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56. *Fao Rome* **1998**, *300*, D05109.
22. Pajura, R. Composting Municipal Solid Waste and Animal Manure in Response To The Current Fertilizer Crisis - A Recent Review. *Science of The Total Environment* **2024**, *912*, 169221. [CrossRef]
23. Smith, M.; Allen, R.G.; Pereira, L.S. Revised FAO methodology for crop water requirements. *Irrig. Drain.* **2000**, *49*, 97–110. [CrossRef]
24. Chaves, M.M.; Flexas, J.; Pinheiro, C. Photosynthesis under drought and salt stress: Regulation mechanisms from whole plant to cell. *Ann. Bot.* **2010**, *103*, 551–560. [CrossRef]
25. Egyptian Meteorological Authority (EMA). Climatic Data for the El-Khatatba Region in Egypt: Means for the Period 2023–2024. 2024. Available online: http://nwp.gov.eg/ (accessed on 2 November 2024).
26. Martínez, J.J.; Melgarejo, P.; Hernández, F. Irrigation regime effects on pomegranate (*Punica granatum* L.) fruit quality. *Agric. Water Mgmt.* **2009**, *96*, 1633–1639.
27. Walker, W.R.; Allen, R.G.; Jensen, M.E. Model for predicting evapotranspiration and irrigation scheduling for pomegranate. *Agric. Water Manag.* **2006**, *82*, 138–157.
28. Lurie, S.; Friedman, H.; Weksler, A. Effects of irrigation and harvesting time on pomegranate fruit quality. *Postharv. Biol. Technol.* **2012**, *65*, 162–168. [CrossRef]
29. Mena, P.; Galindo, A.; Collado-González, J.; Ondoño, S.; GarcíaViguera, C.; Ferreres, F.; Torrecillas, A.; Gil-Izquierdo, A. Sustained deficit irrigation affects the colour and phytochemical characteristics of pomegranate juice. *J. Sci. Food Agric.* **2012**, *93*, 1922–1927. [CrossRef]
30. Porras-Jorge, R.; Aguilar, J.M.; Baixauli, C.; Bartual, J.; Pascual, B.; Pascual-Seva, N. Effect of Deficit Irrigation on Agronomic and Physiological Performance of Pomegranate (*Punica granatum* L.). *Plants* **2025**, *14*, 164. [CrossRef]
31. Bugueño, F.; Livellara, N.; Varas, F.; Undurraga, P.; Castro, M.; Salgado, E. Responses of young Punica granatum plants under four different water regimes. *Cienc. Inv. Agric.* **2016**, *43*, 49–56. [CrossRef]
32. Meshram, D.T. Response of Pomegranate (*Punica Granatum* L.) to Deficit Irrigation System under Field Conditions. *J. Agrometeor.* **2020**, *22*, 126–135.
33. Intrigliolo, D.S.; Bonet, L.; Nortes, P.A.; Puerto, H.; Nicolas, E.; Bartual, J. Pomegranate trees performance under sustained and regulated deficit irrigation. *Irrig. Sci.* **2013**, *31*, 959–970. [CrossRef]
34. Leal, L.d.e.S.G.; Marinho, L.B.; Macário de, G.; Pereira dos, M.É.; Clemente, V.D.; Aires, E.S.; Figueiredo Neto, A. Irrigation Management of Punica Granatum in the Sub-Middle São Francisco River Valley: Morphophysiological Aspects. *Com. Sci.* **2024**, *15*, e4023. [CrossRef]
35. Centofanti, T.; Banuelos, G.S.; Wallis, C.; Ayars, J.E. Deficit irrigation strategies and their impact on yield and nutritional quality of pomegranate fruit. *Fruits* **2017**, *72*, 47–54. [CrossRef] [PubMed]

36. Nasrabadi, M.; Ramezanian, A.; Eshghi, S.; Sarkhosh, A. Chilling and heat requirement of pomegranate (*Punica granatum* L.) trees grown under sustained deficit irrigation. *Sci. Hortic.* **2020**, *263*, 109117. [CrossRef]
37. Laribi, A.; Palou, L.; Intrigliolo, D.; Nortes, P.; Rojas-Argudo, C.; Taberner, V.; Bartual, J.; Pérez-Gago, M.B. Effect of sustained and regulated deficit irrigation on fruit quality of pomegranate cv. 'Mollar De Elche' at harvest and during cold storage. *Agric. Water Manag.* **2013**, *125*, 61–70. [CrossRef]
38. Aydin, Y.; Mikail, N.; Pakyürek, M.; Saltuk, B.; Seven, M. Water-yield relationship of Zivzik pomegranate under deficit irrigation conditions. *Land Reclam. Earth Obs. Surv. Environ. Eng.* **2017**, *6*, 81–86.
39. Dinc, N.; Aydinsakir, K.; Isik, M.; Bastug, R.; Ari, N.; Sahin, A.; Buyuktas, D. Assessment of different irrigation strategies on yield and quality characteristics of drip irrigated pomegranate. *Irrig. Sci.* **2018**, *36*, 87–96. [CrossRef]
40. Martínez-Nicolás, J.J.; Galindo, A.; Griñán, I.; Rodríguez, P.; Cruz, Z.N.; Martínez-Font, R.; Carbonell-Barrachina, A.A.; Nouri, H.; Melgarejo, P. Irrigation Water Saving during Pomegranate Flowering and Fruit Set Period Do Not Affect Wonderful and Mollar de Elche Cultivars Yield and Fruit. Composition. *Agric. Water Manag.* **2019**, *226*, 105781. [CrossRef]
41. Volschenk, T. Effect of Water Deficits on Pomegranate Tree Performance and Fruit Quality—A Review. *Agric. Water Manag.* **2021**, *246*, 106499. [CrossRef]
42. Haleem, A.Y.; Ghieth, W.M.; Hegazy, A.A.H. Performance of Some Pomegranate Cultivars under Different Irrigation levels in North Sinai. *Middle East J. Agric. Res.* **2021**, *9*, 1021–1031. [CrossRef]