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Plant-Growth-Promoting Rhizobacteria as a Sustainable Strategy for Enhancing Quinoa Resilience to Salt Stress in Arid Regions

Fahad N. Al-Barakaha  and Abdulaziz G. Alghamdi * 

Department of Soil Sciences, College of Food and Agriculture Sciences, King Saud University, P.O. Box 2460, Riyadh 11451, Saudi Arabia; barakah@ksu.edu.sa

* Correspondence: agghamdi@ksu.edu.sa; Tel.: +966-562985495

Abstract

Soil salinity and water scarcity are major challenges limiting agricultural productivity in arid and semi-arid regions. Quinoa (a climate-resilient crop) offers potential for sustainable food production under these harsh conditions; however, its growth and yield are often constrained by salt and water stress. This study evaluated the role of plant-growth-promoting rhizobacteria (PGPR) in enhancing *Chenopodium quinoa* Willd performance under deficit irrigation (DI) with saline water. A greenhouse pot experiment was conducted with four irrigation levels (40%, 60%, 80%, and 100% of the growth water requirement, GWR) and two water qualities (fresh water, EC = 0.8 dS m⁻¹; and saline water, EC = 6.0 dS m⁻¹), each tested with and without PGPR inoculation. The results showed that PGPR application significantly ($p < 0.05$) improved quinoa tolerance to salinity, leading to higher biomass, yield, and crop water productivity (CWP) under saline irrigation. Yield reductions were most severe at 40% GWR (53.9% and 82.6% under saline and fresh water, respectively), but PGPR inoculation mitigated yield losses, with increases of 83.3% and 130.8% under 40% and 100% GWR saline irrigation, respectively. Notably, PGPR did not show a clear effect with freshwater irrigation. In addition, inoculated plants exhibited improved nutrient uptake and reduced heavy metal accumulation. Overall, PGPR demonstrated strong potential to enhance salinity resilience and water-use efficiency in quinoa. Future studies should extend these findings under field conditions and investigate the long-term impacts of PGPR on sustainable crop production in saline- and water-limited environments.

Keywords: abiotic stress tolerance; bio-fertilizers; *Chenopodium quinoa* Willd; regulated deficit irrigation



Academic Editor: Mohammad Valipour

Received: 9 September 2025

Revised: 2 October 2025

Accepted: 11 October 2025

Published: 13 October 2025

Citation: Al-Barakaha, F.N.; Alghamdi, A.G. Plant-Growth-Promoting Rhizobacteria as a Sustainable Strategy for Enhancing Quinoa Resilience to Salt Stress in Arid Regions. *Sustainability* **2025**, *17*, 9048. <https://doi.org/10.3390/su17209048>

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1. Introduction

The most crucial element in crop production is the availability of freshwater [1]. Poor irrigation water management is thought to be the primary cause of soil salt deposition, which lowers crop yield on agricultural fields in arid and semi-arid regions [2]. Significantly, salinity affects almost 20% of agricultural soils worldwide [3]. Salinity issues in arid and semi-arid regions are expected to worsen due to climate change [4]. Meanwhile, the global population is projected to reach 9.8 billion by 2050 [5]. This will significantly increase the demand for food and fiber, putting pressure on these countries to boost agricultural production [6].

In Egypt there has been a recent surge in quinoa (*Chenopodium quinoa* Willd) production as a substitute crop that is drought-, salt-, and weather-tolerant [7]. According to Orcutt and Nilsen [8], typical glycophytic crops cannot withstand high soil salinity and

drought stresses. In arid regions that are already at risk from climate change, cereal crops like corn, wheat, barley, and rice cannot thrive in the face of rising soil and water salinity and a shortage of water resources [9]. However, quinoa, as a halophyte, can withstand saline and drought stressors in a variety of situations [3,10]. Quinoa can, therefore, be used as an alternative food crop in arid regions [7,11]. According to Morales et al. [12], quinoa is a grain crop that is native to Andean South America and is a member of a botanical family that is rich in halophytic taxa (44%). Furthermore, according to Cocozza et al. [13], quinoa may produce crop yields comparable to those under normal circumstances and exhibit acceptable resilience to drought and salt stress through stomatal responses and osmotic adaptations. In addition, because the seeds of quinoa are abundant in essential vitamins and amino acids, it has substantial nutritional value [14]. Orcutt and Nilsen [8] reported that quinoa contains the right physiological processes to offer osmoregulation in saline water (~300 mM NaCl or greater). Cocozza et al. [13] reported that quinoa is a crop that can withstand salt and water stress using stomatal responses and osmotic adjustments. This helps to maintain leaf turgor and provide a decent yield in the Mediterranean agro-ecosystem. Aly et al. [3] mention that quinoa has the potential to be salt- and drought-tolerant in terms of biomass production. Furthermore, Eisa et al. [15] reported that quinoa can be cultivated in saline conditions up to 40% salinity of seawater. Long [16] discovered that at a salinity concentration of 50 mM of NaCl, quinoa plant-height recovery was observed. On the other hand, Patel et al. [17] concluded that the salinity caused quinoa plant leaves to accumulate less K^+ and Ca^{2+} while significantly increasing the amounts of Na^+ , Cl^- , and proline.

An environmentally beneficial method of reducing salinity stress is the use of salt-tolerant bacteria [18,19]. Slatni et al. [20] said that under high salinity, inoculation with salt-tolerant plant-growth-promoting rhizobacteria (PGPR) markedly enhanced quinoa growth and physiology, as reflected by greater biomass production, increased root length and lateral root formation, higher proline accumulation, and improved photosynthetic activity. Zaki et al. [21] isolated salt-tolerant bacteria from saline soils in Egypt and evaluated their ability to produce growth-promoting substances under salt stress. They also investigated the combined effects of these bacteria and arbuscular mycorrhizal fungi (AMF) on maize grown under salinity stress. They found that the bioinoculant treatments significantly enhanced maize photosynthetic pigments, growth parameters, NPK (nitrogen, phosphorus, and potassium) uptake, and antioxidant enzyme activity. In contrast, proline accumulation, sodium uptake, and the Na^+/K^+ ratio were reduced. Additionally, AMF colonization in roots and bacterial populations in the rhizosphere were enhanced under salinity stress due to the bioinoculant application.

Water scarcity and the deterioration and salinization of land and water resources are already problems in the arid and semi-arid environments. Thus, studies on quinoa growing under drought and salinity stress will not only add to the body of knowledge but also provide important food and crops to nations located in dry ecosystems. This study hypothesizes that inoculation with plant-growth-promoting rhizobacteria (PGPR) mitigates the negative effects of water deficit and salinity stresses on quinoa plants. Consequently, the primary goal of this study is to evaluate the influence of water deficit and salinity stresses on quinoa (*Chenopodium quinoa* Willd) growth in the presence of plant-growth-promoting rhizobacteria (PGPR). Specifically, this research investigates effects on vegetative metrics, grain yield, nutrient uptake, heavy metal accumulation, and ionic balance. By addressing these aspects, this study contributes to Sustainable Development Goals (SDGs), in particular, SDG 2 (Zero Hunger) through enhancing food security under marginal conditions, SDG 6 (Clean Water and Sanitation) by improving water-use efficiency, and SDG 12 (Responsible Consumption and Production) through promoting sustainable agricultural practices.

2. Materials and Methods

2.1. Soil Analysis

Following the removal of organic matter and lime, the soil texture was determined using hydrometer techniques [22]. However, the EC and pH meters (Test kit Model 1500-20, Cole and Parmer, Vernon Hills, IL, USA) were used to measure the soil salinity (ECe) and pH, respectively, in the soil paste extract [23]. The soil texture was sandy (1.5% clay, 2% silt, and 96.5% sand), and the soil's EC and pH were 15 dS/m and 7.2, respectively. In this study, the soil in each pot was leached to reduce its salinity to 3 dS/m before transplanting the quinoa seedlings. Each pot, with an average surface area of 283.4 cm², received 4.19 cm of water per irrigation, applied daily for 21 days.

2.2. Growth Conditions, Plant Material, and Treatments

A greenhouse pot experiment was conducted at King Saud University (KSU), Riyadh, Kingdom of Saudi Arabia (KSA), using quinoa (*Chenopodium quinoa* Willd.) plants (variety Ames 13747). The seeds used in this study were sourced from a prior cultivation cycle conducted at the King Saud University experimental farm. The quinoa seeds were sown in small plastic containers with moistened vermiculite. For a week, seedlings were given Hoagland solution. Then, one intact plant was transferred to a 1000 mL plastic pot containing sandy soil. The layout of the experiment was completely randomized design with four replicates. The irrigation treatments consisted of four levels of irrigation (40, 60, 80, and 100% of GWR) throughout the experimental period using two types of irrigation water: fresh (tap water, EC = 0.8 dS/m) and saline (EC = 6.0 dS/m). The saline water was prepared using 3.86 gm (66.0 mM) of sodium chloride dissolved in 1 liter of tap water. A strong linear relationship was observed between the weight of NaCl and the electrical conductivity of water (ECw), with an R² value of 0.994. The following equation can be used to prepare NaCl solutions with varying ECw values (Figure 1):

$$\text{EC (dS/m)} = 1.5562 \times [\text{Weight of NaCl (gm)}] \quad (1)$$

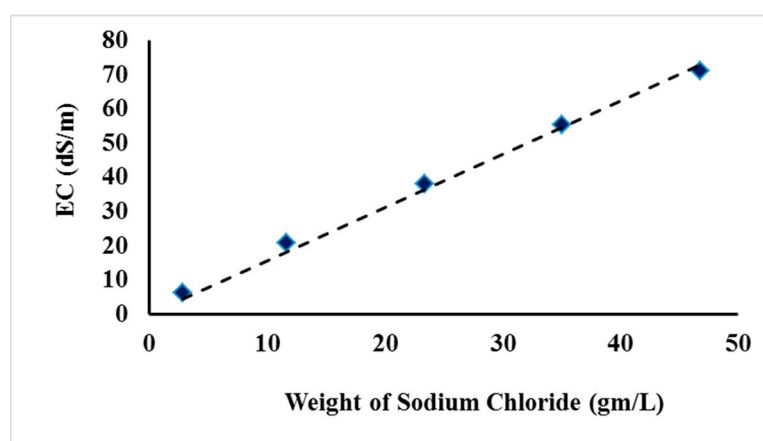


Figure 1. The relationship between the weight of sodium chloride (gm NaCl/L tap water) and water EC (dS/m).

The irrigation scheduling methods were based on a Class A pan evaporation method (Table 1). In addition, soil treatments with plant-growth-promoting rhizobacteria (PGPR) were included in this investigation. The PGPR used in this study included *Azotobacter chroococcum*, *Azospirillum brasilense*, and *Pseudomonas aeruginosa*, identified through cultural, morphological, and biochemical characteristics following standard methods, and confirmed by DNA sequencing at Macrogen, a biotechnology company in South Korea. The bacterial

concentration was approximately 10^7 CFU. Seeds were inoculated using sucrose as an adhesive via seed coating.

Table 1. Experimental design: irrigation treatment using fresh and saline water and PGPR inoculation.

Main Factor	Percentage of GWR	Inoculation Status	Abbreviations
Fresh water	100% of GWR	With inoculation	AIF
		Without	AUF
	80% of GWR	With inoculation	BIF
		Without	BUF
	60% of GWR	With inoculation	CIF
		Without	CUF
	40% of GWR	With inoculation	DIF
		Without	DUF
	100% of GWR	With inoculation	AIS
		Without	AUS
Saline water	80% of GWR	With inoculation	BIS
		Without	BUS
	60% of GWR	With inoculation	CIS
		Without	CUS
	40% of GWR	With inoculation	DIS
		Without	DUS

Azotobacter sp., *Azospirillum* sp., and *Pseudomonas* sp. enhance the germination individually and in combination with each other [24,25]. In this study, there were three stages for the application of phosphate, potassium, and nitrogen fertilizers (solutions) at rates of 50, 50, and 120 kg ha^{−1} (surface pot diameter = 18 cm), respectively. The first dose was given after the pots were transplanted, the second after the fourth leaf appeared (30 days after transplanting), and the third before the inflorescence appeared (65 days after transplanting) [3].

2.3. Crop Evapotranspiration (ET_c) Determination

The following formula was used to compute crop evapotranspiration (ET_c):

$$ET_c = E_o \times K_p \times K_c \quad (2)$$

where E_o is the evaporation from the class A pan in millimeters; K_p is the pan coefficient (which ranges from 0.70 to 0.88, with a common average value of 0.75, following standard pan-to-ET conversion recommendations; see FAO guidelines [26]); K_c is the crop coefficient (1.00 during the mid-season stage and 0.70 during harvest stage according to FAO-56 [26]); and ET_c is the maximum daily crop ET in millimeters. The equations by Allen et al. [26] were used to calculate the K_p and K_c.

The following equations were used to obtain the gross water requirement (GWR) [27]:

$$GWR = ET_c / (1 - LR) \quad (3)$$

$$GWR = (K_c \times E_o \times K_p) / (1 - LR) \quad (4)$$

where LR is the proportion of leaching requirement; and GWR is the gross water demand in millimeters per day.

In accordance with Ayers and Westcot [28], the LR was determined as follows:

$$LR = EC_w / (2 \times \max EC_e) \quad (5)$$

where EC_w is the salinity of irrigation water ($dS\ m^{-1}$); and $\max EC_e$ is the electrical conductivity of the saturated soil extract that will lower the crop yield to zero ($15\ dS\ m^{-1}$ according to Allen et al. [26]).

The computed LR values in this experiment were 0.03 for fresh water and 0.2 for saline water.

2.4. Analysis of the Nutrients and Components of Quinoa

Before being used in chemical tests, the harvested quinoa plants were weighed and separated into shoots and roots. According to Pequerul et al. [29], the shoot samples were washed, oven-dried for two days at $65\ ^\circ C$, ground to pass through a 60-mesh screen, and subsequently digested with hydrogen peroxide (H_2O_2) prior to nutritional and elemental analysis. The H_2O_2 digestion protocol, originally described by Pequerul et al. (1993) [29], involves oxidative digestion of plant material using 30% H_2O_2 under controlled heating, which is widely applied for micronutrient determination in plant tissues.

The ICP-Perkin Elmer Model 4300DV was used to measure the following elements: sodium (Na^+), potassium (K^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), sulfate (SO_4^{2-}), phosphorus (P), cobalt (Co), cadmium (Cd), copper (Cu), chromium (Cr), iron (Fe), nickel (Ni), manganese (Mn), zinc (Zn), and lead (Pb). A total of 0.5 g of powdered plant tissues was mixed with 100 mL of hot water ($60\ ^\circ C$) for three hours in order to determine the Cl^- content. Using a chloridometer (Sherwood Scientific Ltd., Cambridge, UK), 0.5 mL of the extract was used to determine the Cl^- [30].

2.5. Crop Water Production

According to Kijne et al. [31], the crop water productivity is the following ratio of crop yield to volume of applied water:

$$CWP = \text{Yield} / (\text{Water Applied}) \quad (6)$$

Crop water production function (CWPF) is the general term used to describe the relationship between crop yield and water application. When some of the extra water is lost or drains, the CWPF becomes curvilinear. It illustrates the advantage of using water to produce dry matter or yield. The following is the expression for Helweg's [32] quadratic polynomial function:

$$Y_a = b_0 + b_1 W + b_2 W^2 \quad (7)$$

where Y_a is the yield ($m^3\ ha^{-1}$); W is the amount of irrigation water applied; and b_0 , b_1 , and b_2 are fitting coefficients.

The maximum applied water (W_{max}) was determined by differentiating the CWPF (Equation (7)) and equalizing by zero. The maximum predicted yield (Y_{max}) can then be computed by substituting the W_{max} in Equation (7): the slope of the water productivity function against water applied goes to zero as yield approaches its maximum value.

$$\frac{\partial Y}{\partial W} = +b_1 + 2b_2 W = 0 \quad (8)$$

$$W_{max} = \frac{-b_1}{2b_2} \quad (9)$$

$$Y_{\max} = b_0 + b_1 W_{\max} + b_2 W_{\max}^2 \quad (10)$$

2.6. Statistical Analyses

Statistical analysis of quinoa plant data and yields was performed using analysis of variance (ANOVA), along with least significant difference (LSD) and Duncan's multiple range test (DMRT), utilizing SAS software, version 9.4 (SAS Institute Inc., Cary, NC, USA) [33]. The DMRT was used for mean separation because of its higher sensitivity in detecting differences among treatments and its common application in agricultural research, despite being less conservative than Tukey's HSD [34,35].

3. Results and Discussion

3.1. Soil Salinity Removal

This study found that the amount of water ($EC_w = 0.8$ dS/m) required to decrease the soil salinity of sandy soil, under atmospheric temperature ($25\text{--}28$ °C), from 15 dS/m to 3.12 dS/m was ~ 8800 m³/hectare (average pot area = 283.4 cm², depth of applied water for each irrigation event was 4.19 cm, and the irrigation intervals were each day for a period of 21 days). The soil salinity after the first 7 days of leaching was 8.26 dS/m, after 14 days it was 6.01 dS/m, and finally reached 3.12 dS/m after 21 days of irrigation.

3.2. Drought Stress Application

The salinity and drought stress application were conducted after 45 days of transplanting. After 42 days of application, plant drought stress symptoms appeared. The plants irrigated with fresh water clearly suffer from drought for all treatments; on the other hand, when saline water was used, the plants showed more ability to address drought stress for all treatments, with the exception of the 40% irrigation level (Figure 2) [3]. In general, plants exposed to combined salinity and drought stress show reduced wilting, better leaf turgor, and greener foliage compared to plants under drought stress alone. These visible differences suggest that salinity stress may trigger physiological or biochemical mechanisms that enhance the plant's ability to cope with limited water availability (Figure 2) [3,36,37].

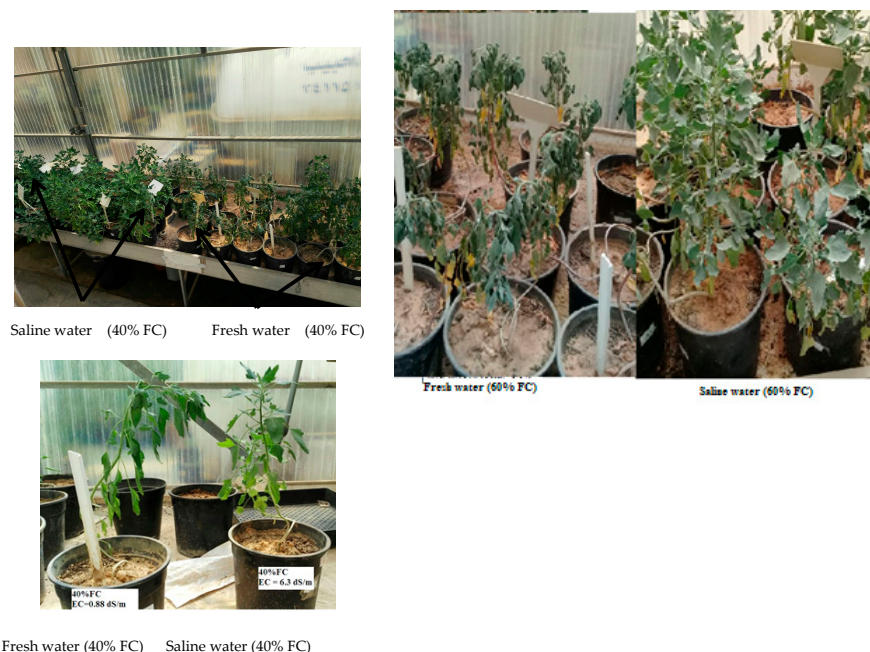


Figure 2. Visual comparison of plant responses under drought and salinity stress conditions, highlighting enhanced drought tolerance in salinity-treated plants. The photos were taken before irrigation.

3.3. Biomass Production

The two main environmental factors limiting agricultural productivity in arid environments are drought and salinity [9]. In terms of biomass production, this study found that quinoa drought tolerance is increased by salt stress (Figures 2–4) [3]. A careful balance between osmotic adjustment and ion buildup is largely responsible for this species' salt tolerance. When quinoa is treated with PGPR in a saline environment, no ion toxicity or deficiencies and osmotic stress appear to be factors. Lower grain production is most likely the outcome of growth reduction brought on by a prolonged salt stress (Figure 5).

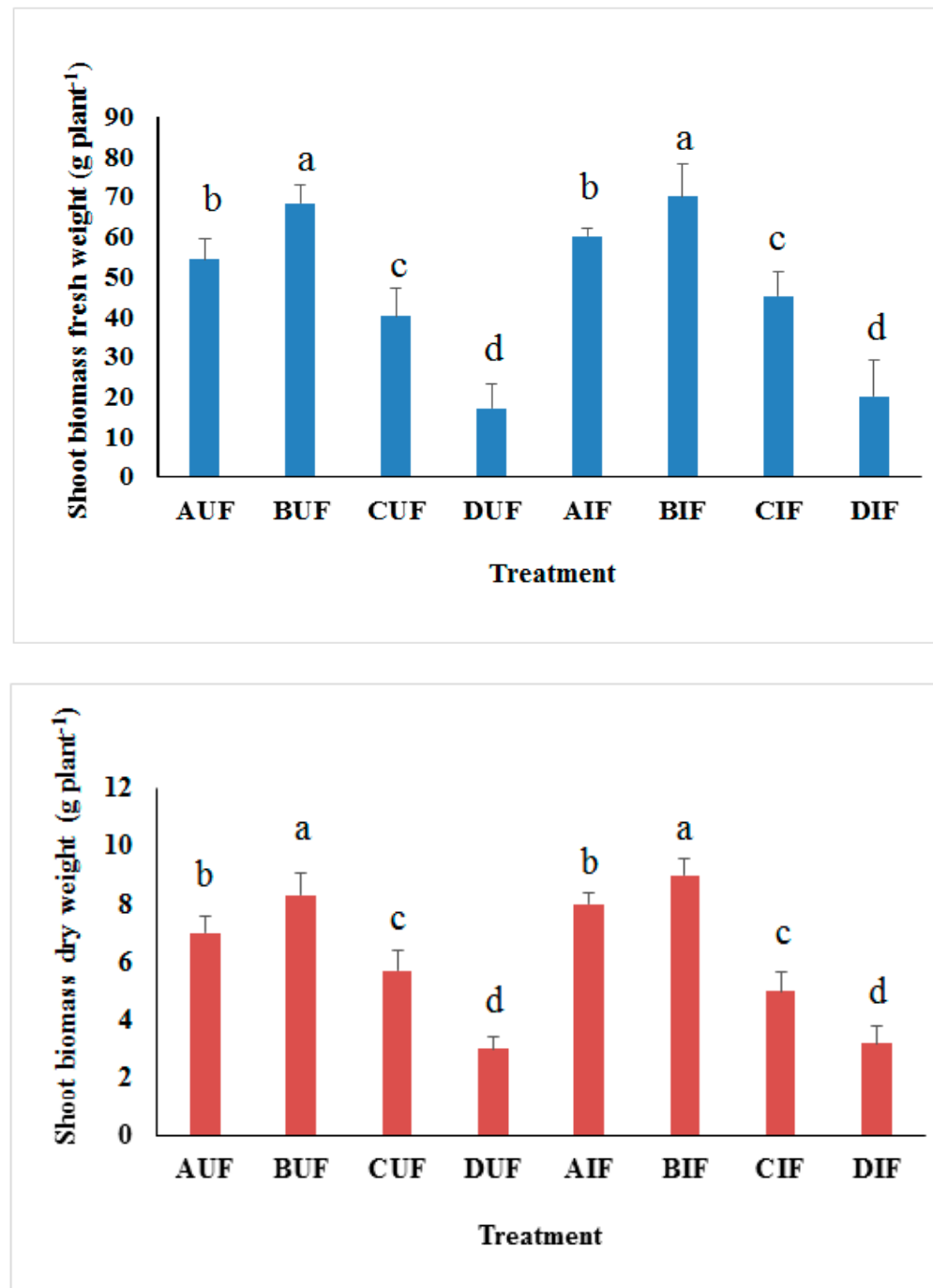


Figure 3. Impact of drought stress and PGPR treatments on quinoa average biomass production. Treatment means with alike letters are not significant by LSD at 0.05 level.

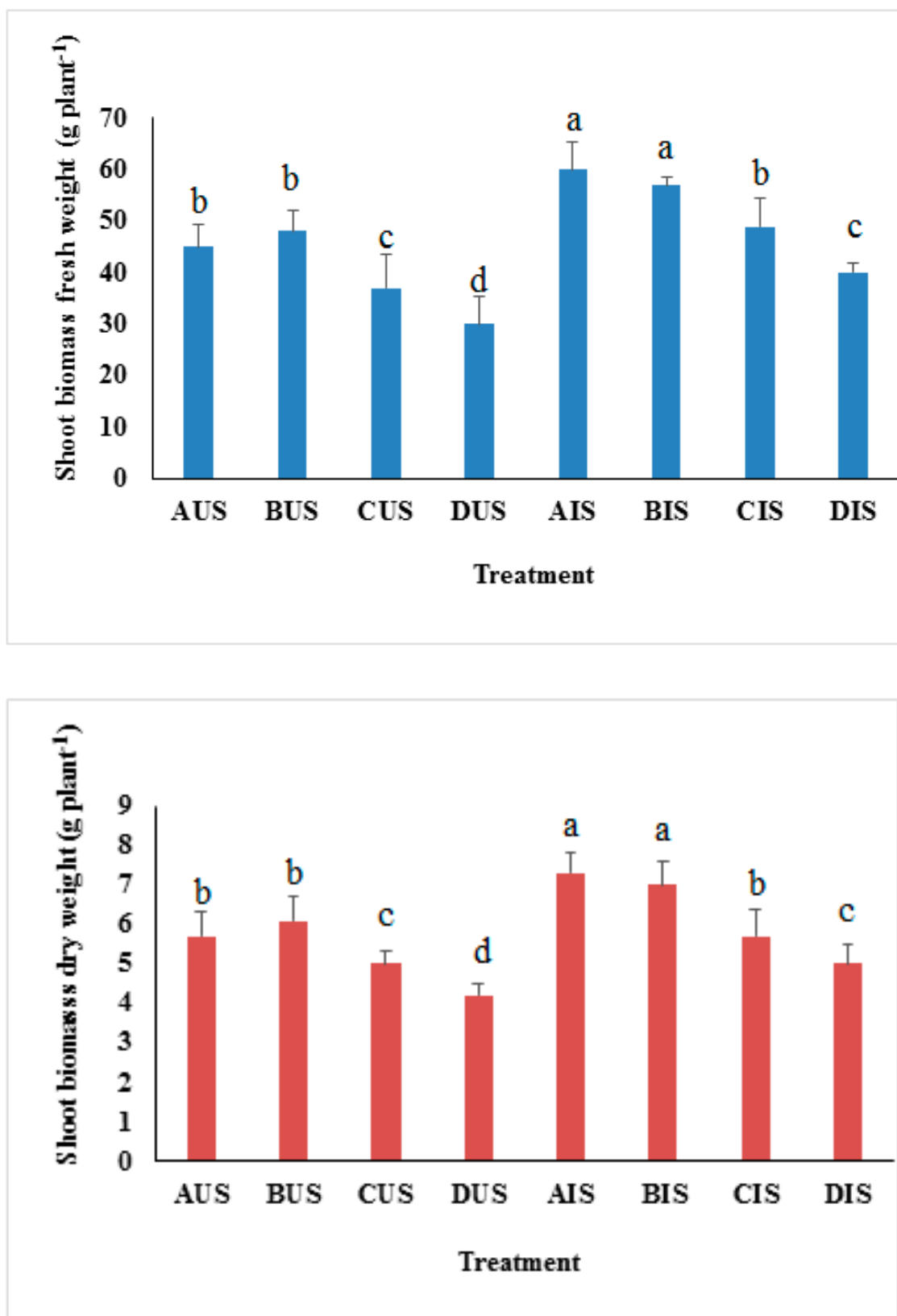


Figure 4. Impact of salinity, drought stresses, and PGPR treatments on quinoa average biomass production. Treatment means with alike letters are not significant by LSD at 0.05 level.

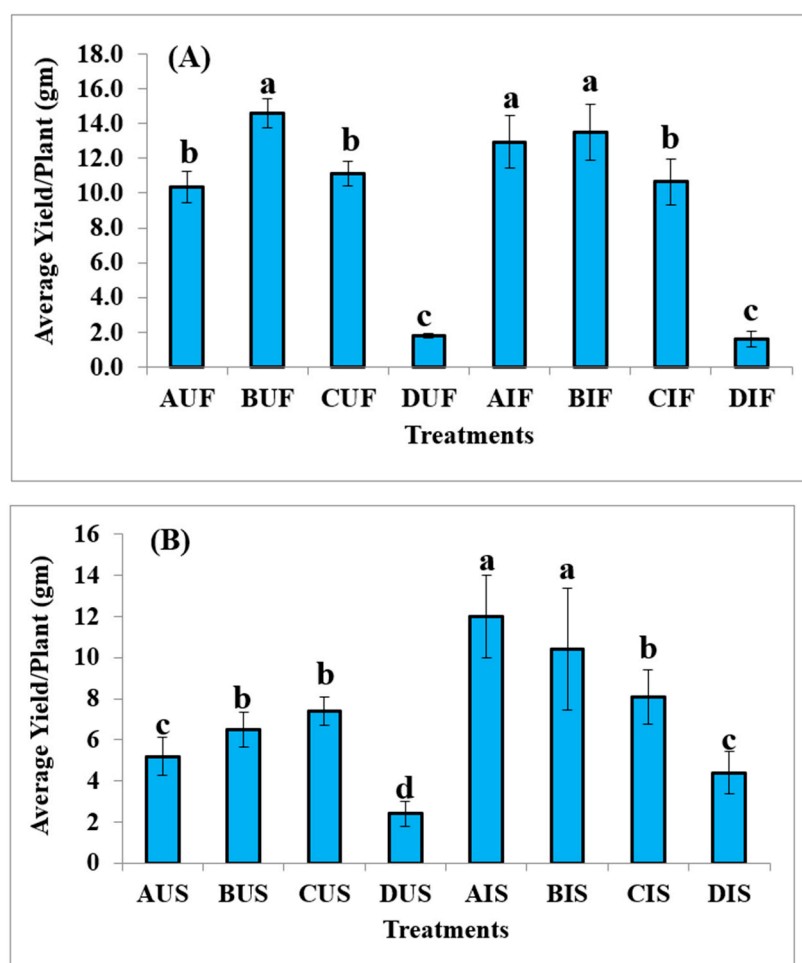


Figure 5. Impact of deficit irrigation and PGPR inoculated on yield of quinoa production using (A) fresh water and (B) saline water. Treatment means with alike letters are not significant by LSD at 0.05 level.

The BIF and BUF treatments had maximum average fresh weight (FW) shoot biomasses of 70.0 and 68.2 g plant⁻¹, respectively, and they also had a maximum average dry weight (DW) of 9.0 and 8.3 g plant⁻¹, respectively (Figure 3). Figure 3 shows that the DUF and DIF had the lowest average fresh weight (FW) shoot biomasses, at 3.0 and 3.2 g plant⁻¹, respectively. According to this study, the biomass of quinoa FW and DW shoots did not significantly increase after PGPR treatment when fresh water was used for irrigation (Figure 3). On the other hand, the quinoa FW and DW shoot biomasses significantly decreased when irrigation water was reduced to 40% [3,18].

When saline water was used for irrigation, the PGPR treatment had a positive effect on increasing quinoa shoot biomass, both in terms of FW and DW. The highest average FW shoot biomass was recorded in the AIS and BIS treatments, with values of 60.0 and 57.0 g plant⁻¹, respectively (Figure 4). In contrast, the lowest FW value was observed in the DUS treatment, at 30.0 g plant⁻¹. A similar trend was observed for DW biomass: AIS and BIS showed the highest average values at 7.3 and 7.0 g plant⁻¹, respectively, while DUS recorded the lowest, at 4.2 g plant⁻¹ [21].

Tables 2 and S1 illustrate the impact of different irrigation regimes (100% and 40% FC), water quality (fresh vs. saline), and PGPR inoculation on the accumulation of heavy metals, macro- and micronutrients, and the ionic balance in plants. Under optimal conditions (100% FC with fresh water), plants exhibited better nutrient uptake and lower heavy metal concentrations, particularly when inoculated with PGPR. For instance, cadmium

(Cd) accumulation was lowest (1.31 mg/100 g) in the non-inoculated control with fresh water but increased significantly under saline- and water-deficit conditions, reaching up to 3.9 mg/100 g. Inoculated treatments generally improved the uptake of essential nutrients like phosphorus (P), calcium (Ca), and magnesium (Mg), and helped reduce sodium (Na) and chloride (Cl) accumulation under stress [20,21]. The potassium to sodium (K/Na) ratio, a key indicator of salinity tolerance, was highest (1.75) in plants under optimal, inoculated conditions and lowest (1.00) in plants exposed to combined water and salt stress without inoculation. In fact, the salt-stressed plants exhibited a decline in the overall K^+/Na^+ ratio. Despite the substantial increase in Na^+ levels, the K^+/Na^+ ratio remained equal or above 1 (Table 2) [3]. This suggests a consistent accumulation of K^+ under saline conditions, especially in the presence of the PGPR (Tables 2 and S1) [3,20,21,38]. Overall, PGPR inoculation enhanced plant resilience by mitigating the adverse effects of salinity and drought, improving nutrient availability, and maintaining a favorable ionic balance.

Table 2. Effect of irrigation regimes, salinity, and PGPR inoculation on elemental concentration in quinoa plants.

Treatments	Cd	Co	Cr	Cu	Fe	Mn	Ni	Pb	Zn	P	Ca	Mg	Na	K	Cl	K/Na
	mg/100 g Plant										g/kg			%		Ratio
AUF	1.31 d *	ND	0.31 c	0.17 c	11.9 a	4.2 c	ND	ND	1.6 c	3.4 e	15.15 c	4.75 c	1.8 e	2.3 e	7.3 c	1.28 b
DUF	2.11 c	ND	0.39 b	0.09 d	10.1 b	4.1 d	ND	ND	0.7 d	2.2 f	16.61 b	3.90 e	2.4 c	2.6 b	9.4 b	1.08 d
AIF	1.34 d	ND	0.29 c	0.18 c	12.0 a	4.7 c	ND	ND	1.8 b	3.5 c	18.91 a	4.77 c	1.6 e	2.8 b	6.4 e	1.75 a
DIF	2.21 c	ND	0.41 b	0.19 c	10.2 b	4.2 d	ND	ND	0.9 d	2.3 f	19.02 a	4.55 c	2.1 c	2.4 e	9.1 b	1.14 c
AUS	3.3 b	ND	0.51 a	0.27 b	9.6 c	7.1 b	ND	ND	2.1 b	3.6 c	11.02 e	5.55 b	3.1 b	3.2 a	7.8 c	1.03 e
DUS	3.9 a	ND	0.42 b	0.28 b	8.1 e	9.2 a	ND	ND	1.8 b	3.8 b	12.03 d	4.70 c	3.62 a	3.61 a	11.0 a	1.00 f
AIS	3.1 b	ND	0.53 a	0.39 a	9.8 c	7.7 b	ND	ND	2.5 a	4.6 a	17.14 b	6.40 a	2.6 c	2.9 b	7.3 c	1.12 c
DIS	3.3 b	ND	0.41 b	0.41 a	8.5 e	9.5 a	ND	ND	1.9 b	3.9 b	15.01 c	4.81 c	3.2 b	3.5 a	9.2 b	1.09 d

* Treatment means with alike letters are not significant by LSD at 0.05 level.

3.4. Yield of Quinoa Plants

The results of the yield of quinoa for different treatments (Table 1) indicated that the PGPR has no significant impact on the yield in the case of using fresh water for irrigation (Figure 5A); however, it significantly increased the yield when saline water was used for irrigation compared to non-inoculated soils for all irrigation treatments (Figure 5B). The highest average yield when fresh water was used for irrigation was obtained in the treatment BUF (14.6 g/plant), and the lowest for the treatment DIF (1.6 g/plant) (Figure 5A). On the other hand, the highest yield when saline water was used for irrigation was for AIS (12 g/plant), and the lowest for DUF (2.4 g/plant). The average yield of quinoa when saline water was used for irrigation in the absence of PGPR inoculation (AUS) was 5.2 g/plant (Figure 5A,B) [3,17]. In general, absolute quinoa yields under saline conditions were lower than those obtained with fresh water. Nonetheless, this study found that PGPR enhanced quinoa yield under saline irrigation by 83.3% in the 40% GWR treatment and by 130.8% in the 100% GWR treatment, while no significant effect was observed under freshwater irrigation [39].

In comparing our results with the existing literature, there is both support and contrast that help to contextualize our findings. For instance, Aly et al. [40] reported quinoa grain yields ranging from 3.5 to 14.1 g plant^{−1} under high salinity stress (EC ~24 dS/m), depending on the genotype, with some lines maintaining relatively high productivity even under severe saline irrigation. This aligns closely with our findings under saline irrigation with PGPR (up to 12 g plant^{−1}), suggesting that PGPR application can help quinoa perform similarly to salt-tolerant genotypes in adverse conditions. Similarly, Elhindi et al. [41]

demonstrated that combining PGPR with phosphogypsum in saline soils significantly improved yield, photosynthesis, and nutrient uptake in quinoa. Though their yield was reported in t/ha, the relative improvement in PGPR-treated plots reflects our observation that PGPR enhanced quinoa productivity under saline water but had minimal impact under freshwater irrigation.

In Egypt, Mahmoud et al. reported that increasing irrigation water salinity from 0 to 20 dS/m led to 12–45% reductions in seed yield, depending on soil type and salinity level [42]. Our results are consistent with this trend, showing a significant yield reduction in non-inoculated plants irrigated with saline water (from 14.6 to 5.2 g plant^{−1}), but importantly, the application of PGPR mitigated this decline (yield increased from 5.2 to 12 g plant^{−1} in inoculated treatments). Similar findings were reported by Slatni et al. [20] who found that halotolerant PGPR enhanced quinoa growth and salt stress resilience by improving physiological performance and nutrient balance under saline irrigation.

Overall, these studies reinforce our conclusion that PGPR inoculation is a promising and cost-effective strategy to improve quinoa productivity in salt-affected environments, particularly in arid regions such as Egypt, where saline irrigation is common. Differences in absolute yields across studies may reflect variation in cultivar, plant density, salinity levels, and environmental conditions.

Numerous investigations explain the role of PGPR (*Azotobacter* sp., *Azospirillum* sp., and *Pseudomonas* sp.) to promote plant growth. These include the following: Sumbul et al. [43] concluded that *Azotobacter* sp. has been shown in numerous studies to be useful in fostering plant development. However, little is known about the precise mechanisms behind its growth-promoting actions. Numerous possible processes have been proposed, including siderophore release, phosphate solubilization, growth hormone synthesis, and nitrogen fixation. However, Coniglio et al. [44] said that *Azospirillum* sp., particularly *A. brasilense*, is known for promoting plant growth through various mechanisms. Gibberellins, abscisic acid, ethylene, nitric oxide (NO), and polyamines are among the numerous growth regulators it generates, in addition to its well-established capacity to fix nitrogen and produce phytohormones like auxins and cytokinins. These compounds have important effects on how plants grow and react to stress. Even though nitrogen fixation and phytohormone synthesis have received the most attention, other aspects such as micronutrient bioavailability, enzyme expression, and competition against phytopathogens are still poorly known. According to Kumar et al. [38], *Pseudomonas* sp. promotes plant growth through a variety of mechanisms, such as phosphate solubilization, siderophore production, modulating phytohormone levels, indole acetic acid, antibiotic synthesis or production, cell-wall-degrading enzyme production, *Pseudomonas* sp. in induced systemic resistance (ISR), and signaling molecules that regulate *Pseudomonas* sp. functions.

It is also necessary to emphasize that the findings concluded that, in comparison to 100% ETc, deficit irrigation using fresh water at 80% ETc was more effective in conserving irrigation water and producing a decent yield. Additionally, a deficit drip irrigation system aids in rationalization by limiting the overuse of fertilizers and pesticides, which in turn lowers pollution in the environment [3].

3.5. Crop Water Productivity (CWP)

Water productivity as a function of yield is expressed by CWP. The findings show that the water regime has a discernible impact on the water productivity of quinoa plants. It was found that the water productivity rises for the water regimes dropped from 100% to 60% GWR. Nonetheless, decreasing irrigation water to 40% GWR led to a significant decrease in water productivity compared to other treatments since it dramatically decreased the final yield. When fresh water was used for irrigation, the 80% and 60% GWR were

found to be the best treatments in terms of water productivity for both non-inoculated and inoculated soils (BUF, CUF, BIF, and CIF), with no significant impact of PGPR inoculation, other than the exception that AIF was found to be more than AUF (Figure 6A). However, when saline water was used for irrigation, the presence of PGPR led to a significant increase in water productivity for all treatments, and the highest values were found for 80% and 60% GWR (BIS and CIS) compared to non-inoculated soils (BUS and CUS) (Figure 6B). The maximum values of CWP were 1.34 and 1.00 kg m⁻³ for CUF and CIS, respectively. Similar results were reported by Alomran et al. [36]; Oweis and Hachum [45]; and Zhang et al. [46]. There are several reasons why DI can raise the ratio of yield to crop water consumption (evapotranspiration). These include (1) lowering water loss from unproductive evaporation; (2) raising the marketable yield to total biomass produced (harvest index); (3) appropriate fertilizer uptake and preventing such unfavorable agronomic conditions as water logging, pest and disease outbreaks, etc. [47,48].

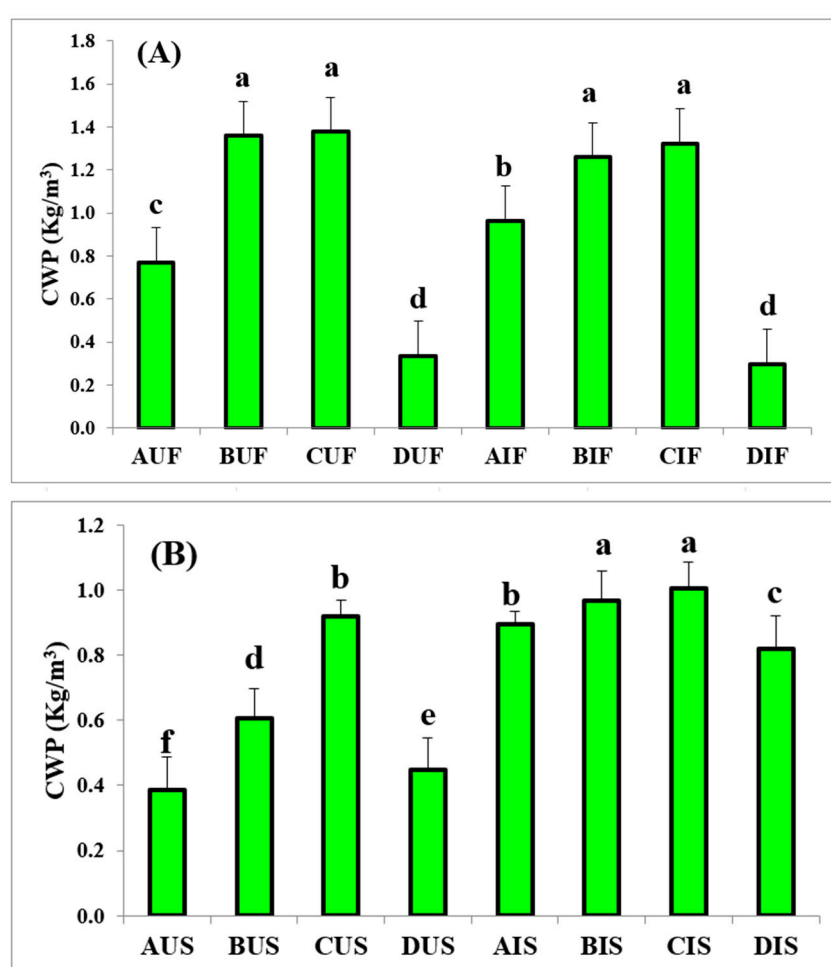


Figure 6. Impact of deficit irrigation on crop water productivity. (A) fresh water and (B) saline water. Treatment means with alike letters are not significant by LSD at 0.05 level.

For each treatment, a polynomial function was fitted between (Y) and (AW) (Figure 7). The maximum yields that were predicted by the crop water production function (CWPF) mathematical analysis were 0.0143, 0.0141, 0.0124, and 0.0074 kg/plant, and the corresponding calculated applied water amounts were 0.0105, 0.0114, 0.0124, and 0.0074 m³ for fresh irrigation water that was inoculated and non-inoculated, and saline irrigation water that was inoculated and non-inoculated, respectively (Table 3). These findings concur with

those published by Zhang and Oweis [49], Al-Harbi et al. [50], Mao et al. [39], and Slatni et al. [20].

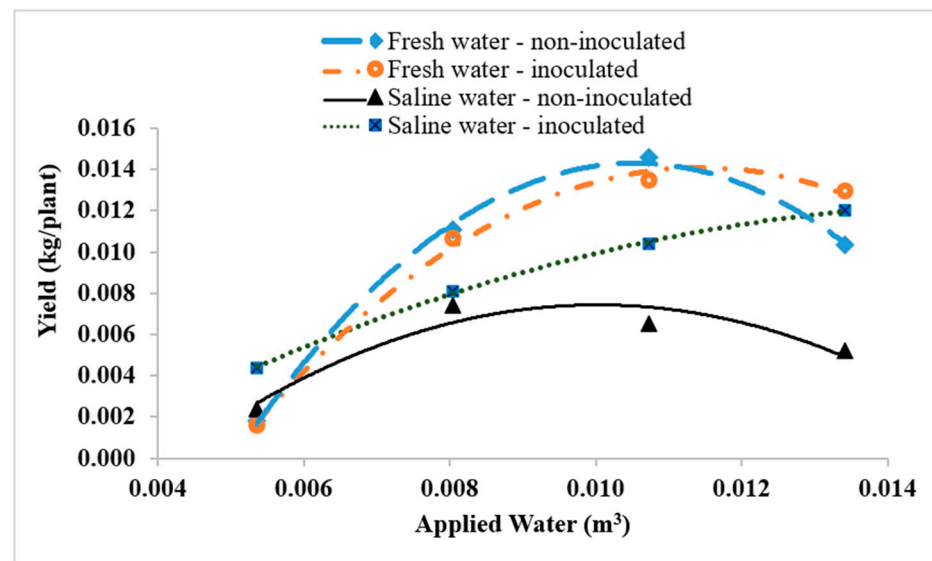


Figure 7. The relationship between the yield of quinoa and applied water within different treatments.

Table 3. Quinoa water production functions based on applied irrigation water.

Treatment	Crop Water Production Function	R ²	Maximum Yield (kg/Plant)	Applied Water (m ³)
Fresh irrigation water (Inoculated)	$Y (\text{Inoculated}) = -334.14(AW)^2 + 7.6478(AW) - 0.0297$	0.996	0.0141	0.0114
Fresh irrigation water (Non-inoculated)	$Y (\text{Non-inoculated}) = -470.23(AW)^2 + 9.9129(AW) - 0.0379$	0.998	0.0143	0.0105
Saline irrigation water (Inoculated)	$Y (\text{Inoculated}) = -72.966(AW)^2 + 2.3058(AW) - 0.0058$	0.9992	0.0124	0.0158
Saline irrigation water (Non-inoculated)	$Y (\text{Non-inoculated}) = -218.9(AW)^2 + 4.3898(AW) - 0.0146$	0.8938	0.0074	0.0100

Lastly, it should be recognized that while this study provides valuable insights into the role of PGPR in mitigating the effects of water and salinity stress on plant nutrient dynamics, several limitations should be acknowledged. First, the experiment was conducted using a single soil type (sand), which, while useful for controlling variables and simulating extreme conditions, does not represent the diversity or complexity of real agricultural soils. This limits the generalizability of the findings to field conditions. Second, the use of a greenhouse pot setup with a small pot size (1000 mL) may restrict root growth and affect stress responses; it introduces artificial environmental controls (e.g., temperature, humidity, and root confinement) that may not reflect the multifactorial stressors encountered in open-field environments. Third, this study lacks physiological measurements such as chlorophyll content, or stomatal conductance, which are critical for understanding the mechanisms underlying PGPR-induced stress tolerance. Without these parameters, the causal link between PGPR application and improved drought or salinity resilience remains largely correlative. Addressing these limitations in future studies would strengthen the applicability and mechanistic understanding of the observed effects.

4. Conclusions

The strategic use of brackish and saline water resources under conditions of freshwater scarcity represents a vital and increasingly necessary approach, particularly in arid and semi-arid regions. This study contributes to the growing body of work advocating for alternative water management strategies, with a particular focus on enhancing water-use efficiency and reducing non-beneficial water losses. A key innovation of this research lies in integrating deficit irrigation techniques with plant-growth-promoting rhizobacteria (PGPR) inoculation under both saline and freshwater conditions—an approach not widely explored in quinoa cultivation. The novelty of this work is reflected in its dual focus: optimizing crop water productivity (CWP) while maintaining yield stability under constrained water availability and demonstrating the potential of microbial inoculants to mitigate the adverse effects of saline irrigation. These findings support the concept that biological interventions can play a critical role in sustainable water management at the field scale, especially for marginal environments. Looking ahead, there is substantial scope for expanding this research. Future studies should explore the long-term impacts of repeated saline water use on soil health, microbial community dynamics, and plant–microbe interactions. Moreover, evaluating the economic feasibility and farmers’ adaptability to such integrated practices will be crucial for widespread adoption. Broader testing across different crops, soil types, and climatic conditions would also strengthen the generalizability of these results. In the context of sustainable agriculture, the integration of PGPR inoculation with optimized irrigation strategies offers a promising pathway to reduce water consumption without severely compromising yield. This approach aligns with global efforts to enhance resource efficiency, support climate resilience, and promote environmentally sound agricultural practices. However, more interdisciplinary field research is needed to fully harness its potential and translate experimental findings into scalable, farmer-friendly technologies. More research is needed to explore the long-term impacts of saline water use on soil health and microbial communities, evaluate the economic feasibility and farmer adoption of PGPR-based irrigation strategies, and expand testing across different crops, soil types, and climatic conditions to enhance the generalizability and scalability of these findings.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/su17209048/s1>, Table S1. ANOVA summary table for elemental concentrations in quinoa plants under different water, salinity, and PGPR treatments.

Author Contributions: Conceptualization, F.N.A.-B. and A.G.A.; methodology, F.N.A.-B. and A.G.A.; formal analysis, F.N.A.-B. and A.G.A.; investigation, F.N.A.-B. and A.G.A.; resources, F.N.A.-B. and A.G.A.; data curation, F.N.A.-B. and A.G.A.; writing—original draft preparation, F.N.A.-B. and A.G.A.; writing—review and editing, F.N.A.-B. and A.G.A.; visualization, F.N.A.-B. and A.G.A.; supervision, F.N.A.-B. and A.G.A.; project administration, F.N.A.-B. and A.G.A.; funding acquisition, A.G.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Ongoing Research Funding program (ORF-2025-825), King Saud University, Riyadh, Saudi Arabia.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in this study are included in the article/Supplementary Materials. Further inquiries can be directed to the corresponding author.

Acknowledgments: The authors would like to thank the Ongoing Research Funding program (ORF-2025-825), King Saud University, Riyadh, Saudi Arabia, for supporting this work.

Conflicts of Interest: The authors declare no conflicts of interest.

List of Abbreviations

Abbreviation	Description
AIF	Soil irrigated with 100% of GWR using fresh water and inoculated with PGPR.
AUF	Soil irrigated with 100% of GWR using fresh water and non-inoculated with PGPR.
BIF	Soil irrigated with 80% of GWR using fresh water and inoculated with PGPR.
BUF	Soil irrigated with 80% of GWR using fresh water and non-inoculated with PGPR.
CIF	Soil irrigated with 60% of GWR using fresh water and inoculated with PGPR.
CUF	Soil irrigated with 60% of GWR using fresh water and non-inoculated with PGPR.
DIF	Soil irrigated with 40% of GWR using fresh water and inoculated with PGPR.
DUF	Soil irrigated with 40% of GWR using fresh water and non-inoculated with PGPR.
AIS	Soil irrigated with 100% of GWR using saline water and inoculated with PGPR.
AUS	Soil irrigated with 100% of GWR using saline water and non-inoculated with PGPR.
BIS	Soil irrigated with 80% of GWR using saline water and inoculated with PGPR.
BUS	Soil irrigated with 80% of GWR using saline water and non-inoculated with PGPR.
CIS	Soil irrigated with 60% of GWR using saline water and inoculated with PGPR.
CUS	Soil irrigated with 60% of GWR using saline water and non-inoculated with PGPR.
DIS	Soil irrigated with 40% of GWR using saline water and inoculated with PGPR.
DUS	Soil irrigated with 40% of GWR using saline water and non-inoculated with PGPR.

References

1. Alghamdi, A.G.; Aly, A.A.; Al-Omran, A.M.; Alkhasha, A.; Alharbi, A. Water conservation in tomato production using deficit irrigation and SALTMed model under greenhouse conditions. *Sci. Afr.* **2024**, *24*, e02185. [\[CrossRef\]](#)
2. Alghamdi, A.G.; Alshami, A.K.; El-Shafei, A.; Alomran, A.M.; Alkhasha, A.; Aly, A.A.; Alharbi, A.R. Evaluating Tomato Performance: A Novel Approach of Combining Full and Deficit Irrigation with Saline Water. *Agronomy* **2024**, *14*, 559. [\[CrossRef\]](#)
3. Aly, A.A.; Al-Barakah, F.N.; El-Mahrouky, M.A. Salinity Stress Promote Drought Tolerance of Chenopodium Quinoa Willd. *Commun. Soil Sci. Plant Anal.* **2018**, *49*, 1331–1343. [\[CrossRef\]](#)
4. Alghamdi, A.G.; Aly, A.A.; Majrashi, M.A.; Ibrahim, H.M. Impact of climate change on hydrochemical properties and quality of groundwater for domestic and irrigation purposes in arid environment: A case study of Al Baha region, Saudi Arabia. *Environ. Earth Sci.* **2023**, *82*, 39. [\[CrossRef\]](#)
5. United Nations (UN). *World Population Prospects 2024: The Twenty Eighth Edition*; UN Department of Economic and Social Affairs, Population Division: New York, NY, USA, 2024. Available online: <https://population.un.org/wpp/> (accessed on 1 April 2025).
6. Zhao, Q.; Huang, J. *Agricultural Science and Technology in China: A Roadmap to 2050*; Springer: Beijing, China, 2011. [\[CrossRef\]](#)
7. FAO. Quinoa for Future Food and Nutrition Security in Marginal Environments. In Proceedings of the International Quinoa Conference, Dubai, United Arab Emirates, 6–8 December 2016.
8. Orcutt, D.M.; Nilsen, E.T. *The Physiology of Plants Under Stress*; John Wiley & Sons, Inc.: New York, NY, USA, 2000.
9. Aly, A.A.; Al-Omran, A.M.; Sallam, A.S.; Al-Wabel, M.I.; Al-Shayaa, M.S. Vegetation cover change detection and assessment in arid environment using multi-temporal remote sensing images and ecosystem management approach. *Solid Earth* **2016**, *7*, 713–725. [\[CrossRef\]](#)
10. Hariadi, Y.; Marandon, K.; Tian, Y.; Jacobsen, S.E.; Shabala, S. Ionic and osmotic relations in quinoa (*Chenopodium quinoa* Willd.) plants grown at various salinity levels. *J. Exp. Bot.* **2011**, *62*, 185–193. [\[CrossRef\]](#)
11. Jacobsen, S.E.; Mujica, A.; Jensen, C.R. Resistance of quinoa (*Chenopodium quinoa* Willd.) to adverse, abiotic factors. *J. Exp. Bot.* **2003**, *54*, 21.
12. Morales, A.J.; Bajgain, P.; Garver, Z.; Maughan, P.J.; Udall, J.A. Physiological responses of *Chenopodium quinoa* to salt stress. *Int. J. Plant Physiol. Biochem.* **2011**, *3*, 1–14. Available online: <http://www.academicjournals.org/ijppb> (accessed on 1 April 2025). [\[CrossRef\]](#)
13. Cocozza1, C.; Pulvento, C.; Lavini, A.; Riccardi, M.; d’Andria, R.; Tognetti, R. Effects of Increasing Salinity Stress and Decreasing Water Availability on Ecophysiological Traits of Quinoa (*Chenopodium quinoa* Willd.) Grown in a Mediterranean Type Agroecosystem. *J. Agron. Crop Sci.* **2013**, *199*, 229–240. [\[CrossRef\]](#)
14. Pulvento, C.; Riccardi, M.; Lavini, A.; Andria, R.D.; Ragab, R. Saltmed model to simulate yield and dry matter for quinoa crop and soil moisture content under different irrigation strategies in south Italy. *Irrig. Drain.* **2013**, *62*, 229–238. [\[CrossRef\]](#)
15. Eisa, S.; Hussin, S.; Geissler, N.; Koyro, H.W. Effect of NaCl salinity on water relations, photosynthesis and chemical composition of Quinoa (*Chenopodium quinoa* Willd.) as a potential cash crop halophyte. *Aust. J. Crop Sci.* **2012**, *6*, 357–368.
16. Long, N.V. Effects of salinity stress on growth and yield of quinoa (*Chenopodium quinoa* Willd.) at flower initiation stages. *Vietnam J. Agri. Sci.* **2016**, *14*, 321–327.

17. Patel, P.R.; Sushil, S.; Kajal, S.S.; Patel, V.R.; Patel, V.J.; Khristi, S.M. Impact of salt stress on nutrient uptake and growth of cowpea. *Braz. J. Plant Physiol.* **2010**, *22*, 43–48. [\[CrossRef\]](#)
18. Szymańska, S.; Lis, M.I.; Piernik, A.; Hryniewicz, K. *Pseudomonas stutzeri* and *Kushneria marisflavi* Alleviate Salinity Stress-Associated Damages in Barley, Lettuce, and Sunflower. *Front. Microbiol.* **2022**, *13*, 788893. [\[CrossRef\]](#)
19. Lami, M.J.; Adler, C.; Caram-Di Santo, M.C.; Zenoff, A.M.; de Cristóbal, R.E.; Espinosa-Urgel, M.; Vincent, P.A. *Pseudomonas stutzeri* MJL19, a rhizosphere-colonizing bacterium that promotes plant growth under saline stress. *J. Appl. Microbiol.* **2020**, *129*, 1321–1336. [\[CrossRef\]](#) [\[PubMed\]](#)
20. Slatni, T.; Ben Ahmed, H.; Belhaj Dali, A. Enhancing Quinoa Growth in Saline Environments Through Salt-Tolerant Rhizobacteria from Halophyte Biotopes. *Physiol. Plant.* **2024**, *176*, e14466. [\[CrossRef\]](#) [\[PubMed\]](#)
21. Zaki, R.M.; Afify, A.H.; Ashour, E.H.; El-Sawah, A.M. Salt-Tolerant Bacteria Support Salinity Stress Mitigating Impact of Arbuscular Mycorrhizal Fungi in Maize (*Zea mays* L.). *Microorganisms* **2025**, *13*, 1345. [\[CrossRef\]](#)
22. Hillel, D. *Soil and Water Physical Principles and Processes*; Academic Press: New York, NY, USA, 1971.
23. Sparks, D.L. *Methods of Soil Analysis. Part 3. Chemical Methods*; SSSA Book Ser. 5; ASA and SSSA: Madison, WI, USA, 1996.
24. Paul, S.; Verma, O.P.; Rath, M.S.; Tyagi, S.P. Effect of *Azotobacter* inoculation on seed germination and yield of onion (*Allium cepa*). *J. Agric. Res.* **2002**, *23*, 297–299.
25. Kurrey, D.K.; Lahre, M.K.; Pagire, G.S. Effect of *Azotobacter* on growth and yield of onion (*Allium cepa* L.). *J. Pharmacogn. Phytochem.* **2018**, *7*, 1171–1175.
26. Allen, R.G.; Pereira, L.S.; Raes, D.; Smith, M. *Crop Evapotranspiration Guidelines for Computing Crop Water Requirements. Irrigation and Drainage Paper 56*; FAO: Rome, Italy, 1998.
27. Cuenca, R. *Hrrigation System Design: An Engineering Approach*; Prentice Hall, Inc.: Englewood Cliffs, NJ, USA, 1989; p. 552.
28. Ayers, R.S.; Westcot, D.W. *Water Quality for Agriculture*; FAO Irrigation and Drainage Paper, No. 29; FAO Irrigation and Drainage: Roma, Italy, 1985.
29. Pequerul, A.; Perez, C.; Madero, P.; Val, J.; Monge, E. A rapid wet digestion method for plant analysis. In *Optimization of Plant Nutrition. Developments in Plant and Soil Sciences*; Frago, M.A.C., Van Beusichem, M.L., Houwers, A., Eds.; Springer: Dordrecht, The Netherlands, 1993; Volume 53. [\[CrossRef\]](#)
30. Adams, M.A.; Richter, A.; Hill, A.K.; Colmer, T.C. Salt tolerance in *Eucalyptus* sp.: Identity and response of putative osmolytes. *Plant Cell Environ.* **2005**, *28*, 772–787. [\[CrossRef\]](#)
31. Kijne, J.W.; Barker, R.; Molden, D. Improving Water Productivity in Agriculture: Editor's Overview. In *Water Productivity in Agriculture: Limits and Opportunities for Improvement*; Kijne, J.W., Barker, R.M.D., Eds.; International Water Management Institute: Colombo, Sri Lanka, 2003; pp. xi–xix.
32. Helweg, O.J. Functions of crop yield from applied water. *Agron. J.* **1991**, *83*, 769–773. [\[CrossRef\]](#)
33. Field, A. *Discovering Statistics Using IBM SPSS Statistics*, 5th ed.; SAGE Publications: Newbury Park, CA, USA, 2018.
34. Steel, R.G.D.; Torrie, J.H. *Principles and Procedures of Statistics: A Biometrical Approach*, 2nd ed.; McGraw-Hill: New York, NY, USA, 1980.
35. Gomez, K.A.; Gomez, A.A. *Statistical Procedures for Agricultural Research*, 2nd ed.; John Wiley & Sons: Hoboken, NJ, USA, 1984.
36. Alomran, M.; Louki, I.I.; Aly, A.A.; Nadeem, M.E. Impact of Deficit Irrigation on Soil Salinity and Cucumber Yield under greenhouse condition in arid environment. *J. Agric. Sci. Technol.* **2013**, *15*, 1247–1259.
37. Harmanto, V.; Babel, M.S.; Tantau, H.J. Water Requirement of Drip Irrigated Tomatoes Grown in Greenhouse in Tropical Environment. *Agric. Water Manag.* **2004**, *71*, 225–242.
38. Kumar, A.; Verma, H.; Singh, V.K.; Singh, P.; Singh, S.; Ansari, W.; Yadav, A.; Singh, P.K.; Pandey, K. *Role of Pseudomonas sp. in Sustainable Agriculture and Disease Management*; Springer: Berlin, Germany, 2017; pp. 195–215. [\[CrossRef\]](#)
39. Mao, X.; Liu, M.; Wang, X.; Hou, C.Z.; Shi, J. Effects of Deficit Irrigation on Yield and Water Use of Greenhouse Grown Cucumber in the North China Plain. *Agric. Water Manag.* **2003**, *61*, 219–228. [\[CrossRef\]](#)
40. Aly, R.; El-Gazzar, N.; Abdel-Rahman, H. Screening of Quinoa Germplasms under High-SAR Saline Water Irrigation in Arid Regions. *Agric. Water Manag.* **2024**, *275*, 108041.
41. Elhindi, K.M.; El-Din, A.S.; Elgorban, A.M. Quinoa Response to Application of Phosphogypsum and PGPR Under Water Stress Associated with Salt-Affected Soil. *Plants* **2022**, *11*, 872. [\[CrossRef\]](#)
42. Mahmoud, A.A.; Abdelgawad, G.; Hegazi, A.M. Effects of Irrigation Water Salinity on Yield and Physiological Performance of Quinoa in Egypt. *Maghreb J. Agric. Sci.* **2021**, *8*, 97–105.
43. Sumbul, A.; Ansari, R.A.; Rizvi, R.; Mahmood, I. *Azotobacter*: A potential bio-fertilizer for soil and plant health management. *Saudi J. Biol. Sci.* **2020**, *27*, 3634–3640. [\[CrossRef\]](#)
44. Coniglio, A.; Mora, V.; Puente, M.; Cassán, F. *Azospirillum* as Biofertilizer for Sustainable Agriculture: *Azospirillum brasilense* AZ39 as a Model of PGPR and Field Traceability. In *Microbial Probiotics for Agricultural Systems: Advances in Agronomic Use*; Zúñiga-Dávila, D., González-Andrés, F., Ormeño-Orrillo, E., Eds.; Springer International Publishing: Cham, Switzerland, 2019; pp. 45–70.

45. Oweis, T.; Hachum, A. Water Harvesting and Supplemental Irrigation for Improved Water Productivity of Dry Farming System in West Asia and North Africa. In Proceedings of the 4th International Crop Science Congress, Held at Brisbane, on the Theme “Crop Science for Diversified Planet”, Brisbane, Australia, 26 September–1 October 2004.
46. Zhang, Y.; Kendy, E.; Yu, Q.; Liu, C.; Shen, Y.; Sun, H. Effect of Soil Water Deficit on Evapotranspiration, Crop Yield, and Water Use Efficiency in the North China Plain. *Agric. Water Manag.* **2004**, *64*, 107–122. [[CrossRef](#)]
47. 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](#)]
48. Steduto, P.; Albrizio, R. Resource Use Efficiency of Field-grown Sunflower, Sorghum, Wheat and Chickpea. II. Water Use Efficiency and Comparison with Radiation Use Efficiency. *Agric. Forest Meteorol.* **2005**, *130*, 269–281. [[CrossRef](#)]
49. Zhang, H.; Oweis, T. Water-yield Relations and Optimal Irrigation Scheduling of Wheat in the Mediterranean Region. *Agric. Water Manag.* **1999**, *38*, 195–211. [[CrossRef](#)]
50. Al-Harbi, A.R.; Al-Omran, A.M.; El-Adgham, F.I. Effect of Drip Irrigation Levels and Emitters Depth on (*Abelmoschus esculentus*) Growth. *J. Appl. Sci.* **2008**, *8*, 2764–2769. [[CrossRef](#)]

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