



Effect of plant growth promoting bacteria on water use efficiency and yield of safflower (*Carthamus tinctorius* L.) under recycled wastewater and deficit irrigation conditions

Hasan ER¹ · Yasemin Kuslu²

Received: 29 July 2025 / Accepted: 10 September 2025

© The Author(s), under exclusive licence to Springer-Verlag GmbH Germany, part of Springer Nature 2025

Abstract

Given the growing and urgent need for strategies to mitigate the negative effects of drought stress in arid and semi-arid regions, a field study was conducted to evaluate the effects of plant growth promoting bacteria (PGPB) treatments with recycled wastewater and fresh water on seed yield and water productivity of safflower (*Carthamus tinctorius* L.) under deficit irrigation levels in 2022 and 2023. In the study, 0% (I0 - rainfed), 25% (I25), 50% (I50), 75% (I75) and 100% (I100) of the evaporation values read from the Class A pan were selected as irrigation levels; Two irrigation waters of different quality were used: recycled wastewater (RW) and fresh water (FW). The PGPB treatments were applied at four frequencies: R0 (no inoculation, control), R1 (single application at sowing), R2 (two applications: at sowing and 10 days after sowing), and R3 (three applications: at sowing, 10 and 20 days after sowing). Evapotranspiration (ETa) values were similar in both water types. The highest plant height, stem diameter, head diameter, 1000 grain weight and seed yield (107.36 cm, 10.52 mm, 28.55 mm, 48.21 g and 173.10 kg da⁻¹) were measured among RW conditions with I100-R3 treatment recorded. In all treatments, WUE and IWUE ranged between 0.27 and 0.56 kg m⁻³ and 0.46 and 1.77 kg m⁻³, respectively, and it was observed that water stress, the number of bacterial treatments and RW treatments WUE and IWUE values increased in both years. Yield response factor (ky) is between 0.30 and 0.37 for RW treatments and 0.35–0.39 for FW treatments. Similar results were observed in ky values of RW and FW treatments. This state is considered more tolerant to water stress. Thus, RW and deficit irrigation treatments can successfully improve productivity by increasing water efficiency under conditions where water resources are limited. However, it was determined that PGPB applications reduced the seed yield loss caused by water stress in the plant.

Introduction

Global climate change causes adverse weather events such as frequent and intense droughts, leading to a significant reduction in renewable water resources, especially in arid and semi-arid regions (Schilling et al. 2020; Wu et al. 2020). This, together with rapidly growing population and

urbanization, significantly increases the demand for fresh water resources (Oskay et al. 2023). Water scarcity in arid and semi-arid regions has become one of the major problems negatively impacting agricultural production and the food industry (Shareef et al. 2018; Saad et al. 2023; Tutar 2024). Protecting and sustainably managing freshwater resources is critical to global food security. In this regard, it is necessary to increase agricultural yield per unit of water and use water resources more efficiently (Ozer et al. 2020).

In order to reduce the pressure on water resources in arid and semi-arid regions, increasing water use efficiency and identifying alternative water resources are of strategic importance. In this context, environmentally friendly and innovative practices such as the use of recycled wastewater in irrigation and deficit irrigation techniques are considered suitable solutions to both save water and contribute to the sustainability of agriculture (Lahlou et al. 2021; Perulli et

✉ Hasan ER
hasaner@bingol.edu.tr
Yasemin Kuslu
ykuslu@atauni.edu.tr

¹ Department of Biosystems Engineering, Faculty of Agriculture, Bingöl University, Bingöl, Turkey

² Department of Agricultural Structures and Irrigation, Faculty of Agriculture, Atatürk University, Erzurum, Turkey

al. 2021). Deficit irrigation is a method of saving water by consciously reducing irrigation water during certain critical periods of plant growth. Many field studies show that this method can maintain or increase plant productivity if applied correctly (Chai et al. 2016; Chand et al. 2020; Ahmadian et al. 2021; Abd El-Mageed et al. 2022).

Reusing wastewater is an effective approach to maximizing available water resources and alleviating water scarcity in the fight against climate change (Yang et al. 2017; Mahjoub et al. 2022). Studies on the use of recycled wastewater in agriculture show that this practice both improves soil properties and has positive effects on crop yield parameters (Abdel-Aziz 2015; Nzediegwu et al. 2019; Bashir et al. 2021; Ammeri et al. 2023). In addition to these strategies, Plant Growth-Promoting Bacteria (PGPB) can live in the root zone of plants, providing direct or indirect positive effects on growth and yield (Alharbi et al. 2022). Plant Growth-Promoting Bacteria (PGPB) enhance plant growth through diverse direct and indirect mechanisms, though not all bacteria possess the same traits (Mondani et al. 2019; Shah et al. 2021). Direct mechanisms include biological nitrogen fixation, nutrient solubilization (phosphorus, potassium), and phytohormone production such as auxins, gibberellins, and cytokinins (Khalifa et al. 2016; Etesami et al., 2020). Nitrogen-fixing PGPB, including *Bacillus* and *Azospirillum* strains, convert atmospheric nitrogen into plant-available forms via nitrogenase, reducing synthetic fertilizer needs (Bouchet et al. 2016; Alori et al. 2017). Phosphate-solubilizing genera such as *Arthrobacter*, *Bacillus*, *Burkholderia*, *Enterobacter*, *Microbacterium*, *Pseudomonas*, *Rhizobium*, *Mesorhizobium*, *Flavobacterium*, and *Serratia* release organic acids to increase P availability (Anand et al. 2016; Riaz et al. 2020). Siderophore-producing PGPB mobilize insoluble iron for photosynthesis, nitrogen fixation, and respiration, while limiting pathogen access (Rezanka et al., 2018; Khoshru et al. 2020; Haider et al. 2024). Indirectly, PGPB suppress pathogens via antimicrobial compounds, hydrolytic enzymes, antibiotics, and resource competition in the rhizosphere (Ulloa-Ogaz et al. 2015; Vejan et al. 2016). Some strains induce systemic resistance through defense hormones like jasmonic acid (Admassie et al. 2021; Yang et al. 2024). ACC deaminase activity reduces ethylene levels under stress, improving tolerance to drought, salinity, and other abiotic factors (Dutta et al. 2015; Mutai et al. 2017; Ilangumaran And Smith 2017). PGPB also enhance root architecture, water uptake, and antioxidant activity, mitigating damage from water scarcity, salinity, and heavy metals (Santos et al. 2018; Mahreen et al. 2023; Gamalero And Glick 2024). Overall, the combined actions of PGPB—from nutrient mobilization and hormone modulation to pathogen suppression and stress alleviation—support sustainable crop production, improve yields, and reduce reliance

on agrochemicals (Paul et al., 2014; Swarnalakshmi et al. 2020; Zarei 2022; Hasan et al. 2024).

Rhizobacteria generally belong to the genera *Micrococcus*, *Pseudomonas*, *Acinetobacter*, *Achromobacter*, *Alcaligenes*, *Arthrobacter*, *Rhizobium*, *Serratia*, *Enterobacter*, *Erwinia*, *Flavobacterium*, *Aereobacter*, *Agrobacterium*, *Bacillus*, *Burkholderia*, *Azospirillum*, and *Xanthomonas* (Khan et al. 2020). *Azospirillum brasilense* promotes plant growth and yield through indole acetic acid (IAA), nitric oxide (NO), and carotenoid synthesis (Fibach-Paldi et al. 2012), while the *Azospirillum* generally improves growth through IAA synthesis (Fukami et al. 2017); *Enterobacter cloacae* and *Achromobacter xylosoxidans* increase photosynthetic rate and yield through ACC deaminase production, reduction of ethylene levels, and nitrogen fixation (Danish et al. 2020); *Bacillus subtilis* DHK strain increases yield through IAA production (Sood et al. 2020); When *Azospirillum brasilense* and *Pseudomonas fluorescens* are applied together, they increase grain yield by enhancing IAA production, ACC deaminase activity, and phosphate solubility (Di Salvo et al. 2018); *Gluconacetobacter diazotrophicus* enhances nutrient uptake by solubilizing nutrients (Sarathambal et al. 2010); *Pseudomonas fluorescens* P1 strain promotes root system development and plant growth by producing auxin (IAA) and ACC deaminase (Zarei et al. 2019). PGPBs have been shown to improve plant adaptation, particularly under abiotic stress conditions such as water stress (Tanveer And Ali 2022; Zarei 2022).

Safflower (*Carthamus tinctorius* L.) is an annual oilseed plant belonging to the Asteraceae family, known for its high oil content (35–40%) and resistance to water stress, and is of global importance (Torabi et al. 2015; Yazdani et al. 2019). Thanks to its taproot structure, safflower can adapt to arid conditions and is an important agricultural crop grown in arid and semi-arid regions (Yeloojeh et al. 2020; Bijanzadeh et al. 2022). Safflower is cultivated in many countries worldwide, including Egypt, Morocco, China, India, and parts of the Mediterranean region (Ekin 2005), and is particularly widespread in regions with high temperatures and low rainfall. This characteristic makes it a suitable crop for arid agricultural systems (Ebrahimian et al. 2019). However, the literature shows that research involving the use of recycled wastewater and PGPB treatments to reduce the sensitivity of safflower to water stress is limited. The aim of this study was to investigate the effects of irrigation of recycled wastewater with plant growth promoting bacteria (PGPB) on grain yield, water-yield relations and water efficiency of safflower at different irrigation levels under semi-arid conditions. In this context, the findings are expected to provide important contributions to sustainable water management and agricultural production in arid and semi-arid areas.

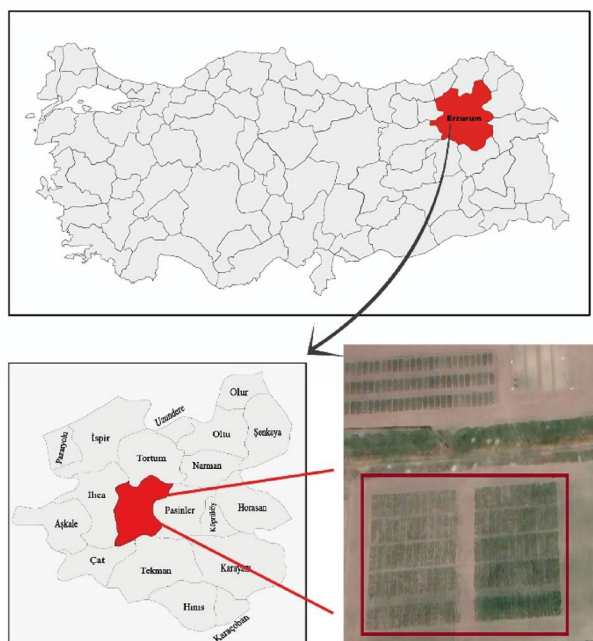


Fig. 1 A general view of the study area

Material and methods

Experimental site

The present study was carried out between May and September 2022 and 2023 in the experimental field of the Application and Research Center for Crop Production at Ataturk University. The study area (39.934°N, 41.236°E) is about 1788 m above sea level and the image of the study area is presented in Fig. 1.

According to long-term climate data (1929–2023), the study area has a semi-arid climate with an annual

precipitation of 431.5 mm and an average annual air temperature of 5.8 °C. July (26.8 mm total rainfall and 19.2 °C average air temperature) and August (17.9 mm total rainfall and 19.5 °C average air temperature) are the driest and hottest months (DMI 2024). Average monthly climate data during the vegetation periods are given in Table 1. The average temperature and total precipitation for the year 2022 are 16.36 °C and 183.7 mm, while the average temperature and total precipitation for the year 2023 are 16.16 °C and 225.1 mm. Precipitation values during the growth periods were measured with a pluviometer installed in the experimental area. Climatic parameters such as average temperature, sunshine duration and relative humidity of the vegetative period are consistent with the long term.

Selected characteristics of the soils are given in Table 2. Both disturbed and undisturbed soil samples were collected from 0 to 30, 30–60 and 60–90 cm depths and analyzed according to the methods presented. The results of the analysis showed that the mean values of pH, electrical conductivity, organic matter, CaCO₃, Total N, P₂O₅ and K₂O were 7.58, 1.38 dS/m, 1.30%, 1.39%, 0.07%, 4.29 kg da⁻¹, 136 kg da⁻¹, respectively. Soil texture was clay loam (36.2% clay, 30.4% silt, 33.4% sand).

Plant material and experimental design

In this study, Dincer, adapted to the ecological conditions of the region, was used as a safflower variety (*Carthamus tinctorius* L.). The plots were sown on May 13, 2022 and May 9, 2023 into account with 2 kg of seeds per decare. According to the soil analysis results, nitrogen (ammonium sulfate) and P (triple superphosphate) fertilizers were applied to all plots at doses of 6 kg N da⁻¹ and 4 kg P₂O₅ da⁻¹, respectively. The plant was harvested at the stage when the leaves were deformed and yellowed. Weeds control were

Table 1 Long term and experimental year's monthly climate data of study site

Years	Months	T _{max} (°C)	T _{min} (°C)	T _{avg} (°C)	Precipitation (mm)	R.H. (%)
1929–2021	May	16.9	4.3	10.7	72.6	62.5
	June	21.8	7.3	14.9	48.6	57.8
	July	26.6	11.1	19.2	26.8	51.5
	August	27.3	11.2	19.5	17.9	48.1
	September	22.7	6.4	14.8	24.2	50.6
2022	May	15.9	2.1	9.1	89.3	67.3
	June	23.9	7.5	15.9	80.4	62.8
	July	28.4	9.5	19.4	5.2	48.1
	August	31.5	11.6	21.9	0	36.2
	September	25.7	4.3	15.5	8.8	42.6
2023	May	16.8	3.9	10.3	99.8	64.6
	June	21.9	7.5	14.8	62	66.6
	July	23.6	10.4	18.0	55.6	57.9
	August	30.9	10.6	21.3	4.4	41.8
	September	25.1	6.9	16.4	3.3	46.3

T_{max}, T_{min} and T_{avg}: maximum, minimum, and average temperature, R.H.: relative humidity.

Table 2 Selected properties of the experimental soil

Properties	Soil depth			Method
	0–30 cm	30–60 cm	60–90 cm	
Clay (%)	36.4	36.2	35.9	(Gee And Or 2002)
Silt (%)	30.1	31.0	30.2	
Sand (%)	33.5	32.7	33.9	
Textural Class	Clay-Loam	Clay-Loam	Clay-Loam	
pH	7.55	7.58	7.61	(Thomas 1996)
EC (dS/m)	1.33	1.39	1.42	(Rhoades 1996)
CaCO ₃	1.51	1.35	1.31	(Loepert And Suarez 1996)
Organic matter (%)	1.61	1.26	1.10	(Nelson And Sommers 1996)
Bulk density (g cm ⁻³)	1.32	1.36	1.32	(Grossman And Reinsch 2002)
Field capacity (P _w , %)	29.80	28.70	25.60	(Cassel And Nielsen 1986)
Wilting point (P _w , %)	16.10	15.43	13.11	

**Fig. 2** Flowering safflower (*Carthamus tinctorius* L.) in the experimental field during the growing season

done by hand-hoeing during the growth period. The harvest was realized on September 19 in 2022 and September 15 in 2023. Figure 2 presents photographs of safflower (*Carthamus tinctorius* L.) in the flowering stage taken from the experimental area.

The field experiments were designed as a randomized complete block split-split plot design with three replicates. Each experimental plot was arranged 8 m long and 1.8 m wide with a total area of 14.4 m² and consisted of four rows spaced 0.6 m apart. A distance of 5 m was set between the FW and RW blocks. In the study, recycled wastewater (RW) and fresh water (FW) treatments constituted the main plots, deficit irrigation levels (I) were assigned to the sub-plots, and plant growth promoting bacteria (PGPB) treatments (R) were assigned to the sub-subplots.

For both water types (RW: recycled wastewater and FW: Fresh water), five different irrigation levels were applied for each water source: 100% of full crop irrigation water requirement, CWR (I100), 25% water less than CWR (I75), 50% water less than CWR (I50), 75% water less than CWR (I25), and rain-fed only (I0) conditions. and four PGPB treatments (R0: Liquid media without bacteria, R1: Liquid media + 1 time bacteria treatment, R2: Liquid media + 2 times bacteria treatment, R3: Liquid media + 3 times bacteria treatment). The PGPB treatments were applied at four frequencies: R0 (no inoculation, control), R1 (single application at sowing), R2 (two applications: at sowing and 10 days after sowing), and R3 (three applications: at sowing, 10 and 20 days after sowing).

Bacteria application

In this study, nine bacterial isolate mixture solutions consisting of *Bacillus megaterium* M-3, *Bacillus megaterium* KBA-10, *Bacillus megaterium* TV-3D, *Bacillus megaterium* TV-91 C, *Bacillus subtilis* TV-17 C, *Bacillus subtilis* TV-12 H, *Bacillus thuringiensis* CP-1, *Pantoea agglomerans* RK-79, *Pantoea agglomerans* RK-92 were prepared and applied (Gökçe and Kotan 2014; Kotan et al. 2014). The atmospheric nitrogen fixation capacity of *Bacillus megaterium* KBA-10, *Bacillus megaterium* TV-3D, *Bacillus subtilis* TV-17 C and *Bacillus thuringiensis* CP-1 isolates were found to be strongly positive. This indicates that these isolates have a high potential to biologically support nitrogen nutrition of plants (Kuan et al. 2016; Stepień et al. 2022). On the other hand, *Bacillus megaterium* M-3 and *Pantoea agglomerans* RK-92 isolates showed strongly positive results in terms of their inorganic phosphate solubilization capacity, indicating that these isolates may play an active role in converting insoluble phosphorus compounds in soil into a form that plants can take up (Singh et al. 2020; Soltani et al. 2025). Studies were carried out on the efficiency of

the isolates in terms of phosphate solubilization, nitrogen fixation, hormone and amino acid production and their effects on plant growth (Li et al. 2017; Silva et al. 2019a). The bacterial strains used in this study were obtained from the culture collection unit of Atatürk University, Faculty of Agriculture, Department of Plant Protection. Bacterial cultures were grown on nutrient agar for routine use and preserved in Luria Broth containing 15% glycerol at -80°C for long-term storage (Kotan et al. 2014; Yildirim et al. 2021). Tryptic soy agar (TSA, Oxoid) and tryptic soy broth (TSB, Oxoid) were used in the experiments. All bacterial isolates were incubated in TSA at 27°C for 24 h. After incubation, single colonies were transferred to 500-mL flasks containing TSB and grown aerobically on a rotating shaker (150 rpm) for 48 h at 27°C . The bacterial suspension was then diluted in sterile distilled water (sdH_2O) to a final concentration of 1×10^8 cfu mL^{-1} as measured with a turbidimeter. The prepared bacterial solution was stored at $+4^{\circ}\text{C}$ until use. For field applications, the solution was applied using a backpack sprayer operating at 2 atmospheres with agitation. The first

application was made directly to the seedbed, followed by two or three subsequent applications at 10-day intervals, depending on the treatment group, at a rate of 400 L/ha to ensure effective colonization and plant interaction. The prepared bacterial solution was first applied to the seedbed; then the application was repeated at 10-day intervals after the planting date to evaluate the effects on plant growth. The same concentration and volume were used for each application. As a control, liquid media, which is known to have no effect on plant growth and in which bacteria live, multiply and feed, was used.

Supply of irrigation water and irrigation system

Irrigation water was supplied to the plots using a drip irrigation system consisting of 16 mm diameter lateral pipes, and the dripper flow rate was 4 L/h at a working pressure of 100 kPa. Diameter of the main pipe and lateral pipes is 50 mm. In the study, FW was obtained from a deep well in the research area and RW was obtained from Erzurum Municipality Biological Wastewater Treatment Plant. The results of the analysis of fresh and recycled wastewater used in irrigation during the years of the study are given in Table 3. It was determined that all quality characteristics of the water used were within the usable limits for soil, plant and irrigation systems (Ayers And Westcot 1989; Kanber and Ünlü 2010).

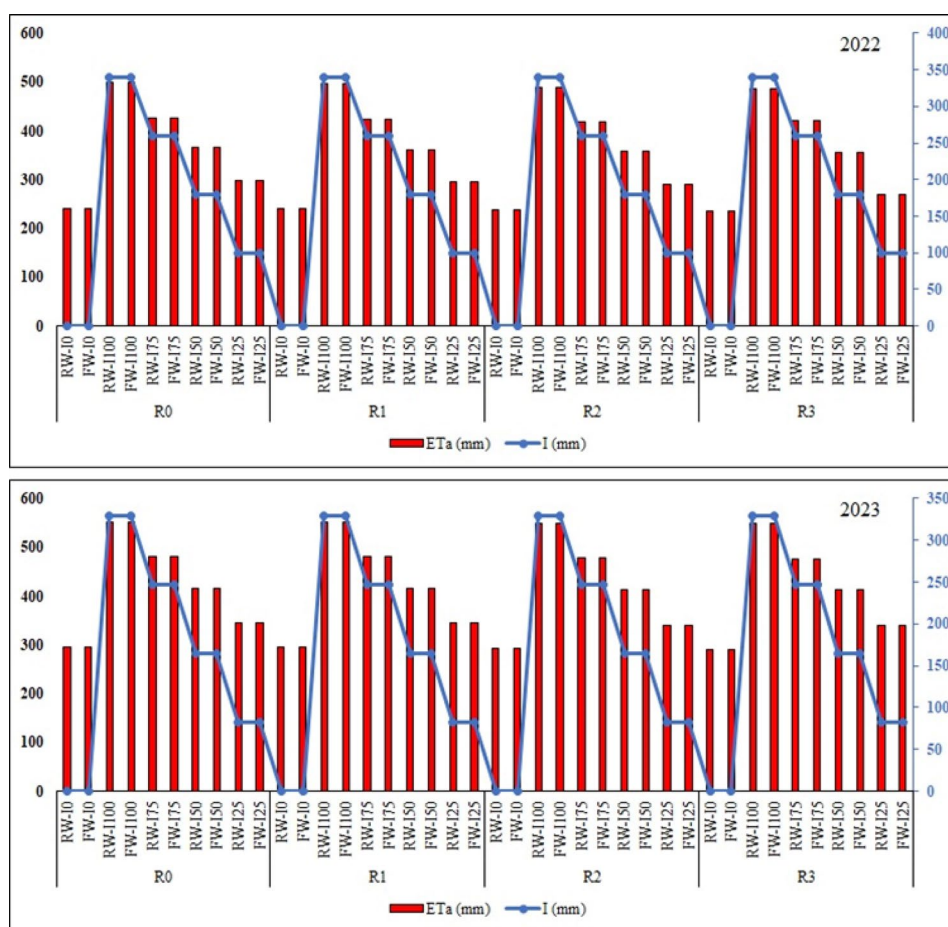
Irrigation water amount (I) and evapotranspiration (ET)

The amount of irrigation water applied and evapotranspiration values obtained from the treatments are given in Fig. 3. Equal amounts of irrigation water were applied in full irrigation with fresh water and recycled wastewater. In 2022, the amount of irrigation water applied to the plots was realized in the range of 100–340 mm, and in 2018 in the range of 82.5–330 mm. In both years of the experiment, planned irrigations were started at the same time and continued until the end of the season. A total of 9 irrigations were made in the first year and 7 irrigations in the second year. The average irrigation interval was calculated as 7 days. ET values varied between 235 and 498 mm in 2022 and 291–552 mm in 2023. In 2022, the highest ET value was observed in the I100-R1 treatment and the lowest value in the I25-R3 treatment, while in 2023, the highest ET value was observed in the I100-R0 and I00-R1 treatments and the lowest value in the I25-R2 and I25-R3 treatments (Fig. 3). The changes in evapotranspiration values of bacteria and irrigation treatments in both experimental years are similar. In the case of full irrigation, evapotranspiration values were similar for RW and FW since the soil moisture difference at the

Table 3 The quality properties of recycled wastewater and freshwater

Properties	Freshwater	Recycled wastewater
pH	8.03	6.92
EC (dS m^{-1})	0.33	0.63
Ca (meq L^{-1})	0.93	2.52
Mg (meq L^{-1})	0.71	0.97
Na (meq L^{-1})	0.33	2.91
K (meq L^{-1})	0.10	0.93
CO_3 (meq L^{-1})	-	-
HCO_3 (meq L^{-1})	1.47	3.96
Cl (meq L^{-1})	0.51	1.92
SO_4 (meq L^{-1})	0.13	0.15
B (mg L^{-1})	0.02	0.06
Fe (mg L^{-1})	0.05	0.04
Cu (mg L^{-1})	-	0.00
Mn (mg L^{-1})	-	0.01
Zn (mg L^{-1})	-	0.06
Pb (mg L^{-1})	-	0.00
Cd (mg L^{-1})	-	-
Cr (mg L^{-1})	-	0.00
Ni (mg L^{-1})	-	0.00
Total Nitrogen (mg L^{-1})	-	7.74
Total Phosphorus (mg L^{-1})	-	1.20
Chemical Oxygen Demand (mg L^{-1})	-	22.33
Biological Oxygen Demand (BOD_5) (mg L^{-1})	-	3.90
Sodium Adsorption Ratio (SAR) (%)	0.40	2.25
Residual Sodium Carbonate (RSC) (meq L^{-1})	-0.17	0.47
% Na	14.55	39.43
Fecal Coliform (colony forming units, CFU 100 mL^{-1})	-	180.33
Total Coliform (colony forming units, CFU 100 mL^{-1})	-	665.00

Fig. 3 Irrigation amount applied (I) and actual evapotranspiration (ETa) in the 2022 and 2023 growing seasons



beginning and end of the vegetation period was close and the irrigation water amounts were equal. In previous studies, Singh (2016) reported that the average ET values of safflower plants grown under different irrigation levels ranged between 239 and 535 mm. Istanbuluoglu et al. (2009) reported that seasonal ET values of summer and winter safflower (*Carthamus tinctorius* L.) varied between 232 and 728 mm under water stress. ET values have been reported to vary between 200 and 1000 mm under different climatic, soil and sowing time conditions and in different varieties (Kar et al. 2007; Lovelli et al. 2007; Istanbuluoglu 2009). While ET values were similar to some previous studies, they were higher or lower than some others. These differences are thought to be due to factors such as climatic conditions, soil properties, irrigation management, safflower variety and cultivation techniques.

Calculation of irrigation water and plant water consumption

The amount of irrigation required for each irrigation was calculated with the following equation. Irrigations were

performed when total evaporation from the Class A pan reached 50 ± 5 mm (Ertek 2011; Ozer et al. 2020).

$$I = E_p \times K_{cp} \times A \quad (1)$$

where; I=amount of irrigation water (liters), A=Plot area (m^2), E_p =Cumulative amount of water that evaporated from the Class-A Pan (mm), K_{cp} = Plant-pan coefficient (K values for different irrigation levels were selected as 1, 0.75, 0.50 and 0.25).

Actual evapotranspiration (ETa) was calculated according to the water budget equation proposed by Allen et al. (1998).

$$ETa = I + P + Cr - Dw - Rf \pm \Delta S \quad (2)$$

where; ETa=Evapotranspiration (mm), I=Amount of irrigation water (mm), Cr=Capillary rise (mm), Dw=Deep percolation (mm), Rf=Amount of runoff (mm) and ΔS =Changes in water content (mm).

The soil of the experimental area was deep and there were no problems with drainage and salinity. Therefore, since there was no capillary rise due to groundwater, the C_p

value was not taken into account in the calculations. Soil moisture above field capacity due to rainfall or irrigation events was considered as deep infiltration. Since the amount of irrigation applied did not exceed the field capacity in all treatments, deep infiltration was disregarded. Since the drip irrigation system was planned and managed correctly, no losses due to surface runoff occurred and therefore the R_f value was excluded from the calculations.

Yield response factor (ky), WUE, and IWUE

Seasonal values of the yield response factor (ky) for each experimental season were determined using the Stewart model Eq. 3 (Doorenbos and Kassam 1979).

$$\left[1 - \frac{Y_a}{Y_m}\right] = ky \cdot \left[1 - \frac{ET_a}{ET_m}\right] \quad (3)$$

where; Y_a =actual yield, Y_m =Maximum yield, ET_a =Actual ET (mm), ET_m =Maximum ET (mm) and ky =Yield response factor.

Irrigation water use efficiency (IWUE) was calculated dividing the grain yield by total irrigation applied during the growing season. Seasonal water use efficiency (WUE) was calculated as follows (Howell 2001; Zou et al. 2021).

$$WUE = \frac{Y}{ET_a} \quad (4)$$

$$IWUE = \frac{Y}{I} \quad (5)$$

where, Y is the total yield (kg da^{-1}) while, ET and I are the total seasonal evapotranspiration and applied irrigation amounts, respectively.

Growth parameters and seed yield

Fifteen plants were randomly sampled from the middle two rows for each plot and then growth yield variables such as plant height, stem diameter, head diameter, 1000 grain weight and grain yield were measured.

Statistical analysis

The data obtained as a result of the research were subjected to analysis of variance with the help of SPSS version 22 package program and compared with analysis of variance (ANOVA) and Duncan multiple comparison test for differences between means.

Results and discussion

Morphological and yield traits of safflower

The average plant height, stem diameter, tray diameter, 1000 grain weight and grain yield values of safflower plants in 2022 and 2023 are given in Table 4. The effects of irrigation levels of treated wastewater and fresh water and number of bacterial treatments on plant height, stem diameter, head diameter, 1000 grain weight and grain yield were found statistically significant at $p < 0.05$ level.

Plant height varied between 75.10 and 107.36 cm, stem diameter 6.83–10.52 mm, head diameter 20.42–28.55 mm, 1000 grain weight 40.87–48.21 g, grain yield 104.11–173.10 kg da^{-1} . The highest plant height, stem diameter, head diameter, 1000 grain weight and grain yield (107.36 cm, 10.52 mm, 28.55 mm, 48.21 g and 173.10 kg da^{-1}) were recorded in I100-R3 treatment with recycled wastewater conditions while the lowest values (75.10 cm, 6.83 mm, 20.42 mm, 40.87 g and 104.11 kg da^{-1}) were recorded in I0-R0 treatment. When the data obtained on plant height, stem diameter and head diameter were analyzed, it was observed that plant height increased as the amount of irrigation water increased. No tendency of the difference in irrigation levels on 1000 grain weight was detected. In both years of the study, the increase in bacterial treatments under recycled wastewater and fresh water conditions increased the values of the head diameter and 1000 grain weight. When examining the average 1000 grain weight values for the 2022–2023 vegetative period, it was determined that the I100-R3 treatment using recycled wastewater had a value 14.07% higher than the I100-R0 treatment. Similarly, for fresh water, the I100-R3 treatment exhibited the highest value, which was 14.74% higher than that of the I100-R0 treatment. In both years, the data on grain yield revealed that an increase in irrigation water quantity and the number of bacterial applications (R0: none, R1: once, R2: twice, R3: three times) resulted in higher grain yield.

It was observed that R2 and R3 treatment values for seed yield were similar to each other. The increase in plant height and stem diameter was found statistically significant as the number of bacterial treatments increased in the rainfed treatment. This resulted in the conclusion that the number of bacterial treatments was important in reducing the negative effects of water stress on the plant. The effects of recycled wastewater and fresh water treatments on plant height, stem diameter and grain yield were found to be statistically significant at $p < 0.05$ level, while the effect on 1000 grain weight was not found to be significant. The effects of recycled wastewater and fresh water treatments on head diameter were found to be statistically significant at $p < 0.05$ level except for I75-R0 and I75-R1 treatments in the first year and

Table 4 Effects of irrigation water quality and bacterial applications on plant height, stem diameter, head diameter, 1000 grain weight and grain yield in safflower plant under different irrigation levels

Irrigation water	Treatment	2022					2023				
		Plant height (cm)	Stem diameter (mm)	Head diameter (mm)	1000-grain weight (g)	Grain yield (kg da ⁻¹)	Plant height (cm)	Stem diameter (mm)	Head diameter (mm)	1000-grain weight (g)	Grain yield (kg da ⁻¹)
Rainfed	I0-R0	75.10cC	6.83eD	25.74bA	41.25bD	104.11dC	78.12dD	7.29eD	20.42eD	42.08bD	116.21eC
	I0-R1	80.85cB	7.51eC	23.83dB	43.07bC	108.12dB	81.24dC	7.58eC	21.30eC	43.93bC	122.69eB
	I0-R2	81.81cB	7.74eB	24.81dC	44.84bB	113.15eA	85.13dB	7.82eB	21.90eB	45.24aB	130.24eA
	I0-R3	85.53cA	7.95eA	22.41dD	45.55bA	114.11eA	89.10dA	8.05eA	22.36eA	46.46aA	128.20eA
RW	I100-R0	95.89aB	8.72aD	26.54aD	42.26aD	170.12aC	103.17aC	9.12aD	25.16aD	41.52cD	165.14aC
	I100-R1	94.49aB	8.88aC	27.12aC	44.66aC	172.12aB	106.39aB	9.56aC	26.64aB	43.32bC	168.25aB
	I100-R2	96.86aB	9.25aB	27.87aB	45.64aB	173.09aA	106.58aB	10.02aB	26.16aC	44.67bB	170.14aA
	I100-R3	98.48aA	9.30aA	28.55aA	48.21aA	173.10aA	107.36aA	10.52aA	26.88aA	46.76aA	170.33aA
	I75-R0	95.93aB	8.41bD	25.88bD	42.90aD	164.16bC	100.87aC	8.78bD	25.09bD	43.76aD	159.87bC
	I75-R1	93.51aB	8.65bC	26.42bC	43.57bC	166.95bB	103.12aB	8.96bC	25.44bC	44.04aC	161.39bB
	I75-R2	95.98aB	8.67bB	27.24bB	44.42bB	168.54bA	103.10aB	9.18bB	25.79bB	45.21aB	164.89bA
	I75-R3	97.56aA	8.81bA	28.45bA	45.51bA	169.94bA	105.23aA	9.41bA	26.28bA	46.42aA	166.66bA
	I50-R0	90.80bC	8.21cD	25.32bD	42.78aD	148.63cC	93.25bC	8.46cD	24.98cD	41.06dD	144.59cC
	I50-R1	92.20bB	8.31cC	26.81bC	42.87cC	150.06cB	95.78bB	8.63cC	25.22cC	42.16cC	146.36cB
	I50-R2	93.30abA	8.41cB	27.37bB	42.91cB	152.11cA	95.89bB	8.91cB	25.30cB	43.20cB	149.36cA
	I50-R3	92.93bA	8.51cA	28.26bA	43.42cA	155.05cA	98.26bA	9.02cA	25.86cA	44.12cA	149.50cA
	I25-R0	88.78bB	7.82dD	24.55cD	41.39bD	145.38cC	86.45cC	8.33dD	24.36dC	40.98dD	140.53dC
	I25-R1	91.02bA	7.92dC	25.42cC	41.52dC	148.47cB	89.98cB	8.46dC	24.39dC	41.10dC	142.28dB
	I25-R2	91.40bA	8.12dB	26.56cB	42.82cB	149.88dA	90.23cB	8.61dB	24.96dB	42.39dB	146.96dA
	I25-R3	90.89bA	8.20dA	27.74cA	45.88bA	150.71dA	92.54cA	8.78dA	25.68dA	45.42bA	146.88dA
FW	I100-R0	88.13aB	8.24aD	26.45aD	42.95aC	158.08aD	91.26aB	8.55aD	23.98aD	43.19aD	151.58aC
	I100-R1	89.33aA	8.36aC	26.91aC	45.07aB	160.92aC	93.25aA	8.72aC	24.24aC	43.72aC	155.63aB
	I100-R2	89.50aA	8.45aB	27.64aA	45.53aB	162.79aB	93.75aA	9.01aB	25.60aB	44.16cB	158.32aB
	I100-R3	89.05aA	8.51aA	27.43aB	48.12aA	165.73aA	94.05aA	9.28aA	25.90aA	46.68aA	158.30aA
	I75-R0	87.21abB	8.15bB	25.86bC	42.34bC	152.10bD	90.75aC	8.26bD	23.52cD	41.62cD	145.59bC
	I75-R1	84.40bB	8.18bB	26.41aB	43.98bB	154.05bC	92.51aB	8.43bC	24.32aC	43.76aC	148.95bB
	I75-R2	89.00aA	8.26bA	26.71cB	42.52dB	155.03bB	93.21aA	8.61bB	24.51bB	44.47bB	152.14bA
	I75-R3	88.43aA	8.28bA	27.44aA	44.03cA	156.03bA	93.60aA	8.88bA	24.74bA	46.12bA	153.66bA
	I50-R0	87.17abB	7.83cB	25.62bC	42.04bC	146.05cD	86.28bC	7.98cD	23.88bD	41.66cD	131.31cD
	I50-R1	84.13bC	7.86cB	26.22bB	42.74bB	148.03cC	88.12bB	8.25cC	23.92bC	42.31bC	134.14cC
	I50-R2	88.20aA	7.94cA	27.32bA	43.82cB	149.03cB	88.04bB	8.43cB	24.46cB	43.08dB	137.17cB
	I50-R3	85.70abB	7.96cA	27.11bA	44.35cA	150.01cA	90.10bA	8.64cA	24.68cA	43.91cA	139.91cA
	I25-R0	84.83bA	7.76dB	25.24cD	41.28cC	138.03dD	82.23cC	7.52dD	23.03dD	40.87dD	126.17dC
	I25-R1	82.48bB	7.78dB	26.05bC	41.26cC	139.01dC	84.58cB	7.78dC	23.15cC	41.50cC	129.48dB
	I25-R2	87.20bA	7.85dA	26.34dB	43.73cB	142.01dB	85.27cB	7.99dB	23.64dB	42.64eB	133.87dA
	I25-R3	82.56cB	7.85cA	27.24bA	44.06cA	144.01dA	87.34cA	8.13dA	24.10dA	45.98bA	132.74dA

Letters followed in each row (small letters) shows differences between irrigation levels, while letters in columns (capital letters) shows differences between bacterial treatments. Mean differences were tested at the level of $p \leq 0.05$.

in all treatments in the second year. When I100-R3 with the highest plant height was analyzed, it was calculated that RW treatment increased the average plant height by 10.58% and 14.15%, the average stem diameter by 9.40% and 13.36%, and the grain yield by 4.45% and 7.59% in 2022 and 2023, respectively, compared to the FW treatment. The results of the present study were similar with the findings in the literature. Recycled wastewater treatments had positive effects on plant growth compared to fresh water (Hashem And Qi 2021; Nemera et al. 2021; El Khoumsi et al. 2024).

For example, Mousavi and Shahsavari (2014) and Quemada et al. (2016) reported that stem diameter and grain yield increased, and it was emphasized that these changes may be due to the nitrogen content (Safi-naz And Shaaban 2015; Lu et al. 2015; Vergine et al. 2017). Yazdani et al. (2018) and Demir and Sahin (2017) reported that recycled wastewater treatment increased fruit diameter, Yazdani et al. (2019) and Moradi et al. (2015) reported that it increased 1000 grain weight and this was statistically significant.

Irrigation using RW can lead to increased plant growth compared to irrigation using FW. The reason for this increase is the high nutrient content of the wastewater, especially the nitrogen contribution. However, when irrigation restrictions are imposed, plant growth may decrease. This is associated with reduced water and nutrient input to the soil. These results suggest that wastewater utilization can be a useful alternative in areas where water resources are scarce or limited. Bacteria treatments also had a positive effect on plant height. The effect of this additive was greater than in FW. It is believed that the combination of plant growth-promoting bacteria can facilitate the uptake of plant nutrients (Cheng et al. 2025). The fact that the RW content is rich in nitrogen and phosphorus (Sengupta et al. 2015) and the bacterial combination used contains nitrogen and phosphorus solubilizing bacteria may have accentuated this positive difference (Khan And Bano 2016; Sarawaneeyaruk et al. 2019). Similarly, many researchers have shown that the increase in plant height is due to high nutrient contribution under irrigation conditions with wastewater use (Hajihashemi et al. 2020; Shah et al. 2022). In addition, many studies have been carried out on the decrease in plant height due to water stress (Kermani And Asadi 2018; Bhattarai et al. 2020; Rady et al. 2021).

Chand et al. (2020) reported that the stem diameter of tomato plants grown at different irrigation levels decreased as the water constraint increased. Rawashdeh (2017) and Ebrahimian et al. (2019) reported that maximum 1000 grain weight was obtained under full irrigation conditions. Shah-rokhnia and Sepaskhah (2017) reported that water stress negatively affected grain yield in safflower plants grown under partial root dryness conditions. In accordance with our study, different researchers reported that water stress applications decreased grain yield (Yeloojeh et al. 2020; Saad et al. 2023). Different studies have reported that water stress has a negative effect on plant growth (Abd El-Mageed et al. 2022; Li et al. 2022). Ayrıca Turan et al. (2014) ve Ijaz et al. (2018) PGPR treatments increased stem diameter in plants under drought stress. Samancioglu et al. (2016) reported that drought conditions created under different irrigation levels negatively affected the growth of cabbage plants. However, they found that the application of PGPR to plants was effective in enhancing tolerance to the adverse effects of drought stress. Lack et al. (2013) reported that the effect of bacterial inoculation on 1000 grain weight was statistically significant. In addition, Saeidi et al. (2018) found that the effect of different doses of chemical fertilizer and nitrogen and phosphorus solubilizing bacteria applications on 1000 grain weight of safflower plant was statistically significant. Ekin (2020) evaluated the cultivation of safflower plant under irrigated and dry conditions with *Bacillus megatorium* M3 and *Bacillus subtilis* OSU142 strains that

promote plant growth, and it was reported that rhizobacteria applications increased head diameter and grain yield. Khademian et al. (2019) stated that grain yield of safflower plant decreased as water stress increased, and *Azotobacter*+*Azospirillum* applications caused positive improvements in grain yield. The findings of the present study suggest that recycled wastewater and PGPR can increase plant tolerance to drought stress and that these practices can be an important tool for sustainable agriculture.

Water use efficiency (WUE) and irrigation water use efficiency (IWUE)

Average WUE and IWUE values of safflower plants for the experimental years are given in Figs. 4 and 5, respectively. In terms of two-year average values, the effect of irrigation levels of RW and FW and the bacterial treatments on WUE and IWUE values were found significant at $p < 0.05$ level. In all treatments, WUE and IWUE varied between 0.27 and 0.56 kg m^{-3} and $0.46\text{--}1.77 \text{ kg m}^{-3}$, respectively. The highest WUE and IWUE values were obtained in the I25-R3 treatment of RW, while the lowest values were observed in the I100-R0 treatment of FW. In both years of the experiment, R0 and R1 and R2 and R3 treatments of RW and FW treatments showed statistically similar characteristics on WUE and IWUE. It was observed that WUE and IWUE values increased with increasing water stress and bacterial treatments in both years of the experiment.

WUE and IWUE values in the first year of the study were higher than the second year values. This is due to the fact that although the yield values obtained in both vegetative periods for WUE are similar, the seasonal rainfall amounts are different, which affects the evapotranspiration, and for IWUE, the amount of irrigation water applied in the second year is less than the first year. In the first year, the highest WUE was obtained at I25, which was 21.95% higher than I0. However, in the second year, WUE values of I25 and I0 subjects were close to each other. It is thought that this situation is due to the high yield values and seasonal rainfall amount of the I0 subject in the second year. According to the average values of two years, the IWUE value of I25-R3 RW treatment was 228% higher than I100-R0 FW treatment. IWUE values were calculated higher compared to WUE values. In this direction, it can be said that the main source of water consumption of plants is irrigation water.

In both years of the study, recycled wastewater source WUE and IWUE values were higher than fresh water conditions. Considering that soil fertility increases during irrigation due to the nutritive properties of recycled wastewater, the higher WUE values obtained with the use of RW were found to be statistically significant. In addition, recycled wastewater WUE values were 7.31%(R0), 9.52%(R1),

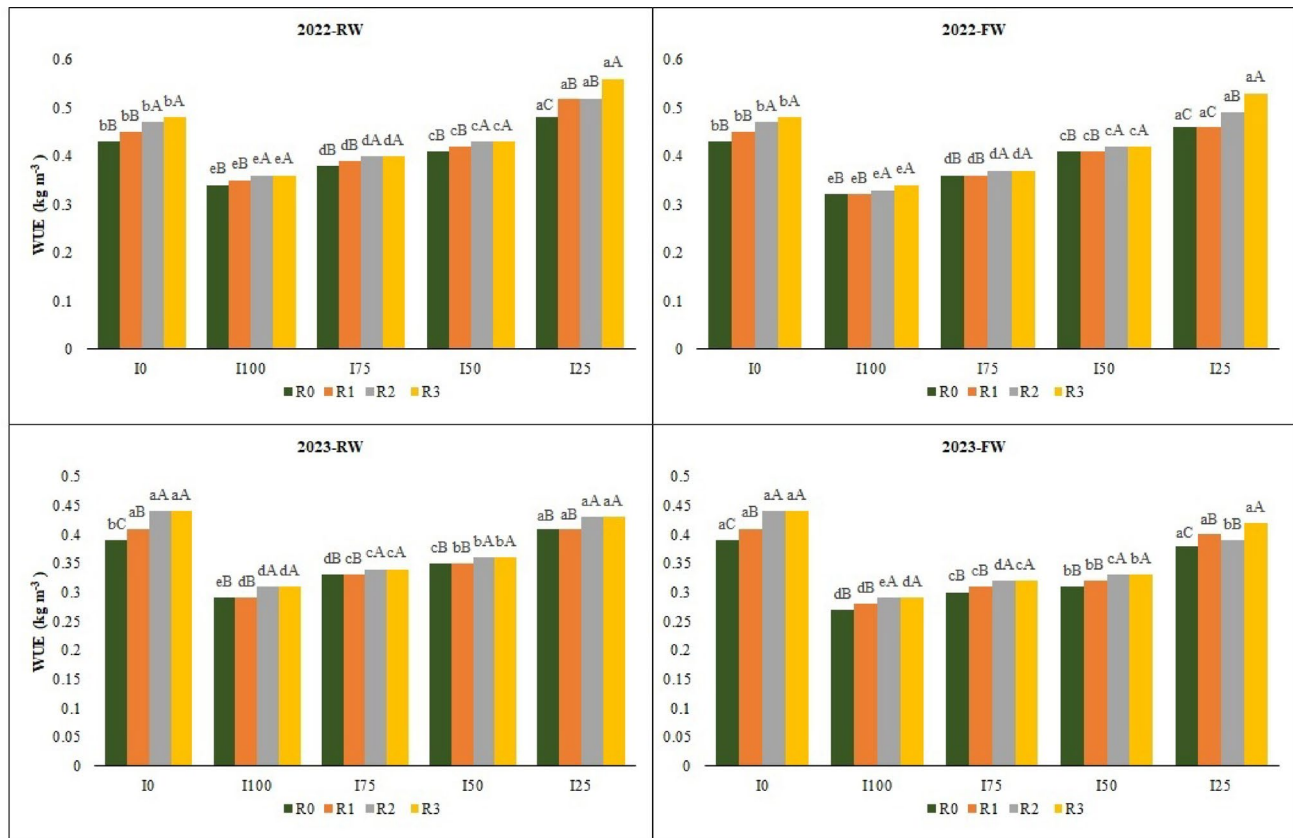


Fig. 4 Water use efficiency (WUE) with bars indicating plus 95% confidence for all years and treatments. Small letters indicate differences between irrigation levels, while capital letters indicate differences between bacterial treatments, mean differences were tested at the level of $p \leq 0.05$

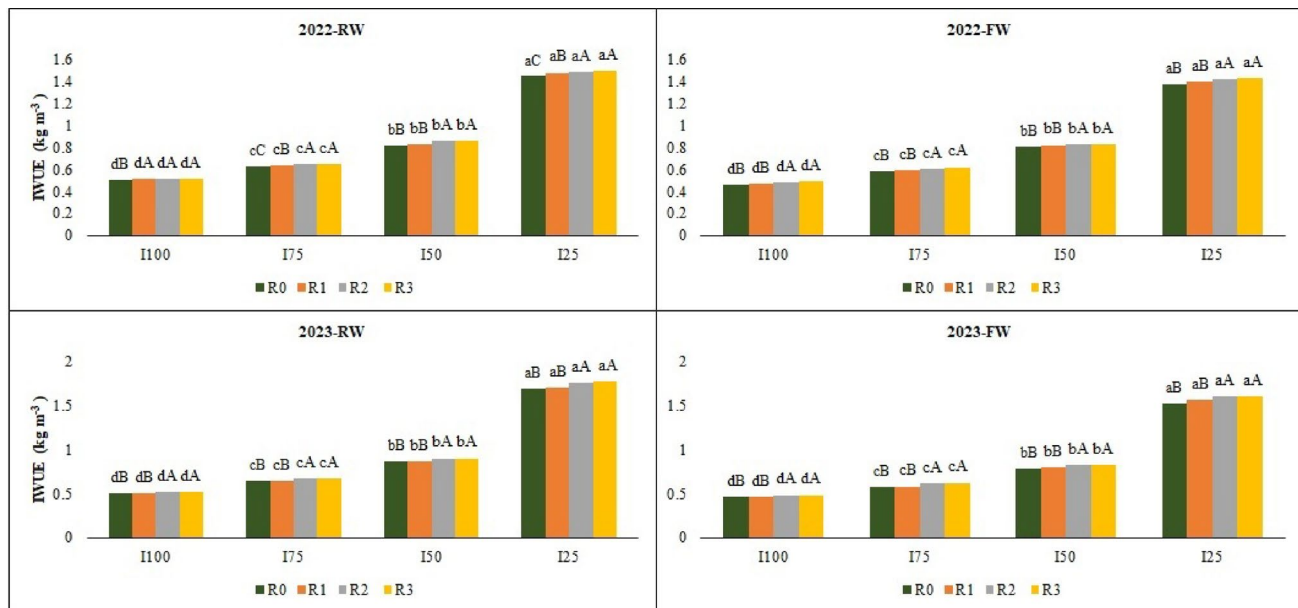


Fig. 5 Irrigation water use efficiency (IWUE) with bars indicating plus 95% confidence for all years and treatments. Small letters indicate differences between irrigation levels, while capital letters indicate differ-

ences between bacterial treatments, mean differences were tested at the level of $p \leq 0.05$

6.81%(R2) and 6.52%(R3) higher than fresh water, respectively. RW treatments achieved higher IWUE and WUE values, indicating that they may have increased productivity by improving soil fertility. In water restriction experiments conducted on different plant species under Erzurum conditions, similar findings to those obtained in this study were reported (Kuslu et al. 2014; Ors et al. 2016). Similarly, Erice et al. (2010) found that different levels of drought reduced WUE values in alfalfa plants. When the studies on different crops and irrigation treatments are examined, it can be said that WUE and IWUE values generally increase with decreasing irrigation level under deficit irrigation conditions. (Marsic et al. 2012; Lerna And Mauromicale 2020; Yu et al. 2020). In a lettuce trial conducted in Erzurum, it was determined that *Bacillus megaterium* TV-6D and *Bacillus subtilis* TV-12 H treatments increased WUE by reducing the negative effects of deficit irrigation (Sahin et al. 2015). Similarly, higher WUE and IWUE values were reported in soybean plants inoculated with bacteria (Karakaya and Ödemiş 2019). In addition, it has been reported that RW provides higher WUE and IWUE values compared to FW. (Rao et al. 2016; Shareef et al. 2018; Chand et al. 2020; Ghassemi et al., 2020).

Relationships between water-yield and yield response factor (ky)

Crop yield exhibited a relative yield loss ($1 - Y_a/Y_m$) that increased proportionally to the relative evapotranspiration deficit ($1 - E_t a/E_t m$) depending on water stress (Fig. 6). The average values for k_y , 2022 and 2023 were determined as 0.35, 0.37, 0.35 and 0.30 for R0, R1, R2 and R3 under RW conditions, respectively, while the values for FW conditions were determined as 0.35, 0.37, 0.36 and 0.39, respectively. Similar results were observed in the k_y values of RW and FW applications. These findings appear to be strongly related to the application of different irrigation levels. Water

stress at I50 level was severe enough to reduce grain yield more than relative evapotranspiration deficit in all treatments. This is due to the fact that the grain yield values obtained in the I50 treatment and the I25 treatment are similar. According to the results obtained, all treatments have a k_y value less than 1. In this case, crops with a k_y value less than 1 are considered more tolerant to water stress, as yield loss under water deficit conditions is lower than the reduction in evapotranspiration (Yavuz et al. 2020). These findings are consistent with studies in the literature (Pejić et al. 2009). For example, the k_y values of maize grown under treated and fresh water conditions were determined to range between 1.19 and 1.77, with higher k_y values observed in RW treatments compared to FW treatment (Cakmakci and Sahin 2021). The winter maize grown in Brazil exhibited high sensitivity with a k_y value of 1.22 (Silva et al. 2019b). The k_y values of maize grown under water-restricted conditions were determined to range between 0.66 and 0.77, indicating a sensitivity to water stress varying from high to moderate (Zou et al. 2021). Similarly, Smith and Steduto (2012) calculated k_y and reported that it varied between 0.20 and 2.30 across different growth stages. These k_y values serve as an important guide for irrigation management and crop planning, contributing to improved water use efficiency and optimized yield predictions.

Safflower grain yields were closely related to ET and applied irrigation water amounts in both years. For all treatments, significant linear regression was observed between crop ET and applied irrigation water amounts and grain yield (Figs. 7 and 8). The equations and coefficients of determination defining the relationships between ET (Fig. 6) and applied irrigation water (Fig. 8) and grain yield in all treatments are indicated in the relevant figures. In general, studies on water-yield relationships have reported linear relationships between ET and the amount of irrigation water applied and yield (Kuşcu et al., 2015; Shareef et al. 2018; Sezen et al. 2019a, b; Yavuz et al. 2020).

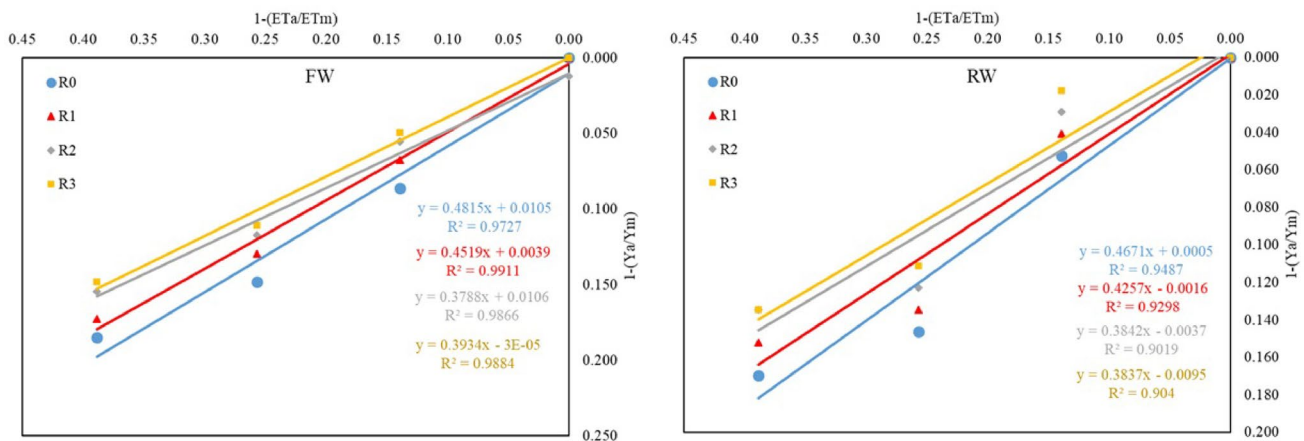


Fig. 6 Relationship between relative evapotranspiration deficit $1 - (E_t a/E_t m)$ and relative yield decrease $1 - (Y_a/Y_m)$ (confidence level $p < 0.05$)

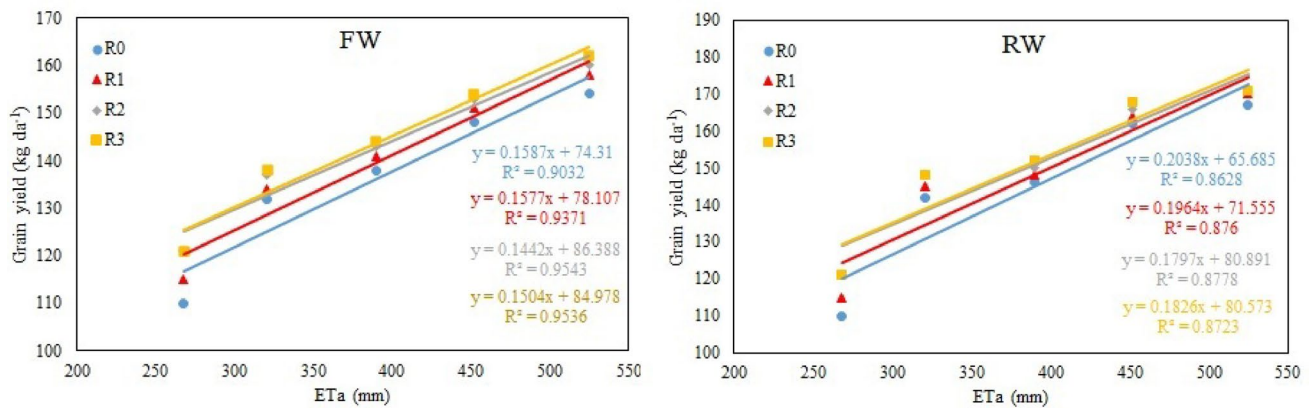


Fig. 7 Relationship between grain yield with evapotranspiration (confidence level $p < 0.05$)

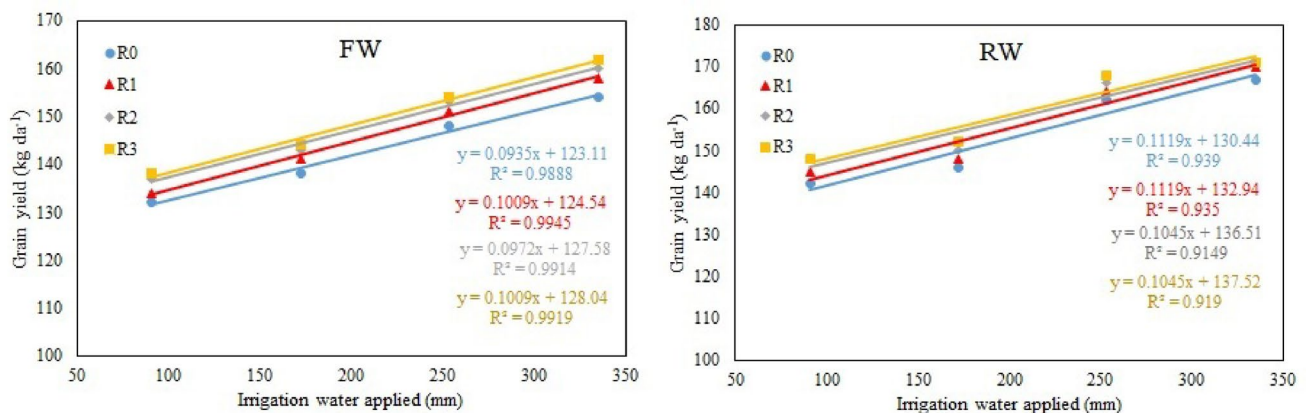


Fig. 8 Relationship between grain yield with irrigation water applied (confidence level $p < 0.05$)

Conclusions

This study was conducted during the 2022 and 2023 growing seasons in Erzurum Province, Turkey, to evaluate the effects of recycled wastewater applied through drip irrigation at different irrigation levels, combined with plant growth-promoting bacteria (PGPB), on the yield, water-yield relationships, and water use efficiency of safflower (*Carthamus tinctorius* L.).

When the two-year average values were examined, it was determined that the RW of the I100 topic increased the plant height by 12.41% and the stem diameter by 11.23% compared to the FW. The RW increased grain yield by 5.98% in the I100 treatment compared to the FW. When examining the two-year average of non-irrigated conditions, the R3 treatment increased seed yield by 9.98% compared to the R0 treatment. Overall, the results indicated that RW applications, different irrigation water levels, and the bacterial treatments significantly affected the yield of safflower. Considering the average of both experimental years, the I25 treatment under RW showed 14% yield reduction, while achieving a 244 mm irrigation water savings and an

85% increase in IWUE. In FW, the I25 treatment showed a 14.66% yield reduction, while achieving the same 244 mm irrigation water savings and an 83.23% increase in IWUE.

These findings are significant for conserving water resources and promoting sustainable water management in agriculture, particularly in arid and semi-arid regions with limited water availability. To this end, the expansion of agricultural production systems that use water efficiently, the implementation of water-saving methods, especially limited water production techniques, and the promotion of recycling and reusing water are essential. The increasing water demand, high costs associated with natural water resources, and advancements in reclamation technologies make wastewater reuse an attractive option both environmentally and economically.

Acknowledgements This study is derived from the PhD thesis conducted by Hasan Er under the supervision of Prof. Dr. Yasemin KUŞLU. This study was supported by Project No: FCD-2022-10339, funded by the Scientific Research Coordination Unit of Atatürk University. This study was supported by project number 1250450 under the TÜBİTAK 1002-B Rapid Support Program.

Author contributions All the authors contributed equally to this work.

Funding No external funding was received for this study.

Data availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interest The authors declare no competing interests.

References

- Abd El-Mageed TA, Rady MO, Abd El-Wahed MH et al (2022) Consecutive seasonal effect on yield and water productivity of drip deficit irrigated sorghum in saline soils. *Saudi J Biol Sci* 29(4):2683–2690. <https://doi.org/10.1016/j.sjbs.2021.12.045>
- Abdel-Aziz R (2015) Impact of treated wastewater irrigation on soil chemical properties and crop productivity. *J Water Resour Arid Environ* 4(1):30–36
- Admassie M, Wold-Hawariat Y, Alemu T (2021) Characterization and diversity of plant growth promoting endophytic and rhizosphere bacteria isolated from the rhizosphere and tissues of pepper and their effect on plant growth promotion and disease suppression. <https://doi.org/10.21203/rs.3.rs-422729/v1>. of phytophthora capsici
- Ahmadian K, Jalilian J, Pirzad A (2021) Nano-fertilizers improved drought tolerance in wheat under deficit irrigation. *Agric Water Manage* 244:106544. <https://doi.org/10.1016/j.agwat.2020.106544>
- Alharbi K, Rashwan E, Hafez E et al (2022) Potassium humate and plant Growth-Promoting microbes jointly mitigate water deficit stress in soybean cultivated in Salt-Affected soil. *Plants* 11(22):3016. <https://doi.org/10.3390/plants11223016>
- Allen RG, Pereira S, Raes D et al (1998) Crop evapotranspiration, guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper No.56, Rome
- Alori ET, Dare MO, Babalola OO (2017) Microbial inoculants for soil quality and plant health. Sustainable agriculture reviews. Springer International Publishing, Cham, pp 281–307. https://doi.org/10.1007/978-3-319-48006-0_9
- Ammeri RW, Hidri Y, Souid F et al (2023) Improvement of degraded agricultural soil in an arid zone following short-and long-term treated municipal wastewater application: A case study of Gabes perimeter, Tunisia. *Appl Soil Ecol* 182:104685. <https://doi.org/10.1016/j.apsoil.2022.104685>
- Anand K, Kumari B, Mallick MA (2016) Phosphate solubilizing microbes: an effective and alternative approach as biofertilizers. *Int J Pharm Pharm Sci* 8(2):37–40
- Ayers RS, Westcot DW (1989) Water quality for agriculture, FAO Irrigation and Drainage Paper-29 Rev.1, Rome, Italy
- Bashir S, Qayyum MA, Husain A et al (2021) Efficiency of different types of biochars to mitigate Cd stress and growth of sunflower (*Helianthus* L.) in wastewater irrigated agricultural soil. *Saudi J Biol Sci* 28(4):2453–2459. <https://doi.org/10.1016/j.sjbs.2021.01.045>
- Bhattarai B, Singh S, West CP et al (2020) Effect of deficit irrigation on physiology and forage yield of forage sorghum, Pearl millet, and corn. *Crop Sci* 60(4):2167–2179. <https://doi.org/10.1002/csc2.20171>
- Bijanazadeh E, Moosavi SM, Bahadori F (2022) Quantifying water stress of safflower (*Carthamus tinctorius* L.) cultivars by crop water stress index under different irrigation regimes. *Heliyon* 8(3):e09010. <https://doi.org/10.1016/j.heliyon.2022.e09010>
- Bouchet AS, Laperche A, Bissuel-Belaygue C et al (2016) Nitrogen use efficiency in rapeseed. A review. *Agron Sustain Dev* 36(2):38. <https://doi.org/10.1007/s13593-016-0371-0>
- Cakmakci T, Sahin U (2021) Improving silage maize productivity using recycled wastewater under different irrigation methods. *Agric Water Manage* 255:107051. <https://doi.org/10.1016/j.agwat.2021.107051>
- Cassel DK, Nielsen DR (1986) Field capacity and available water capacity. *Methods of Soil Analysis*. <https://doi.org/10.2136/sssabookser5.1.2ed.c36>
- Chai Q, Gan Y, Zhao C et al (2016) Regulated deficit irrigation for crop production under drought stress. A review. *Agron Sustain Dev* 36:1–21. <https://doi.org/10.1007/s13593-015-0338-6>
- Chand J, Hewa G, Hassanl A et al (2020) Evaluation of deficit irrigation and water quality on production and water productivity of tomato in greenhouse. *Agriculture* 10(7):297. <https://doi.org/10.3390/agriculture10070297>
- Cheng Y, Shi X, Narayanan M et al (2025) Enhancing nutrient uptake efficiency in *Zea mays*: the role of plant growth-promoting bacteria in modifying root characteristics and mobilizing soil nutrients. *J Sci Food Agric* 105(9):5030–5039. <https://doi.org/10.1002/jsf.a.14233>
- Danish S, Zafar-ul-Hye M, Mohsin F et al (2020) ACC-deaminase producing plant growth promoting rhizobacteria and Biochar mitigate adverse effects of drought stress on maize growth. *PLoS ONE* 15:e0230615. <https://doi.org/10.1371/journal.pone.0230615>
- Demir AD, Sahin U (2017) Effects of different irrigation practices using treated wastewater on tomato yields, quality, water productivity, and soil and fruit mineral contents. *Environ Sci Pollut Res* 24:24856–24879. <https://doi.org/10.1007/s11356-017-0139-3>
- Di Salvo LP, Cellucci GC, Carlino ME et al (2018) Plant growth-promoting rhizobacteria inoculation and nitrogen fertilization increase maize (*Zea Mays* L.) grain yield and modified rhizosphere microbial communities. *Appl Soil Ecol* 126:113–120. <https://doi.org/10.1016/j.apsoil.2018.02.010>
- DMI (2024) Turkish state meteorological service, Ankara. www.mgm.gov.tr/veridegerlendirme/il-ve-ilceleristatistik.aspx?k=undefined&m=ERZURUM (Accessed on 2 December 2024)
- Doorenbos J, Kassam AH (1979) Yield response to water FAO irrigation and drainage paper No. 33. FAO, Rome
- Dutta J, Handique P, Thakur D (2015) Assessment of culturable tea rhizobacteria isolated from tea estates of assam, india for growth promotion in commercial tea cultivars. *Front Microbiol*. <https://doi.org/10.3389/fmicb.2015.01252>
- Ebrahimian E, Seyyedi SM, Bybordi A et al (2019) Seed yield and oil quality of sunflower, safflower, and sesame under different levels of irrigation water availability. *Agric Water Manage* 218:149–157. <https://doi.org/10.1016/j.agwat.2019.03.031>
- Ekin Z (2005) Resurgence of safflower (*Carthamus tinctorius* L.) utilization: A global view. *J Agron* 4(2):83–87
- Ekin Z (2020) Field evaluation of rhizobacterial inoculants in combination with humic substances to improve seed and oil yields of safflower (*Carthamus tinctorius* L.) under irrigated and rainfed conditions. *Appl Ecol environmental Res* 18(5):6377–6403
- El Khoumsi W, Essiba W, Basir I et al (2024) Effect of treated wastewater irrigation on ornamental plants: case study of Lantana and Hibiscus, Morocco. *World Water Policy* 10(1):280–296. <https://doi.org/10.1002/wwp2.12164>
- Erice G, Louahlia S, Irigoyen JJ, Sanchez-Diaz M, Avise JC (2010) Biomass partitioning, morphology and water status of four alfalfa genotypes submitted to progressive drought and subsequent recovery. *J Plant Physiol* 167:114–120
- Ertek A (2011) Importance of Pan evaporation for irrigation scheduling and proper use of crop-pan coefficient (Kcp), crop coefficient

- (Kc) and Pan coefficient (Kp). *Afr J Agric Res* 6:6706–6718. <http://doi.org/10.5897/AJAR11.1522>
- Etesami H, Adl SM (2020) Plant growth-promoting rhizobacteria (PGPR) and their action mechanisms in availability of nutrients to plants. *Phyto-Microbiome stress Regul.* https://doi.org/10.1007/978-981-15-2576-6_9
- Fibach-Paldi S, Burdman S, Okon Y (2012) Key physiological properties contributing to rhizosphere adaptation and plant growth promotion abilities of *Azospirillum brasilense*. *FEMS. Eur Microbiol Soc* *Microbiol Lett* 326:99–108. <https://doi.org/10.1111/j.1574-6968.2011.02407.x>. Fed
- Fukami J, Ollero FJ, Megias M et al (2017) Phytohormones and induction of plant-stress tolerance and defense genes by seed and foliar inoculation with *Azospirillum brasilense* cells and metabolites promote maize growth. *Amb Express* 7:1–13. <https://doi.org/10.1186/s13568-017-0453-7>
- Gamalero E, Glick B (2024) Use of plant growth-promoting bacteria to facilitate phytoremediation. *Aims Microbiol* 10(2):415–448. <https://doi.org/10.3934/microbiol.2024021>
- Gee GW, Or D (2002) Particle-Size Analysis. *Methods of Soil Analysis*. Wiley, pp 255–293. <https://doi.org/10.2136/sssabookser5.4.c12>
- Ghassemi Sahebi F, Mohammadrezapour O, Delbari M, KhasheiSiuki A, Ritzema H, Cherati A (2020) Effect of utilization of treated wastewater and seawater with Clinoptilolite-Zeolite on yield and yield components of sorghum. *Agric Water Manage* 234:106117
- Gökçe AY, Kotan R (2014) Buğday kök çürüklüğüne neden olan *Bipolaris sorokiniana* (Sacc.) fungusunun PGPR ve antagonist bakteriler kullanılarak kontrollü koşullarda biyolojik mücadele imkânlarının araştırılması. Türkiye V. Bitki Koruma Kongresi (Antalya, Türkiye (Turkish))
- Grossman RB, Reinsch TG (2002) Bulk Density and Linear Extensibility. *Methods of Soil Analysis*. <https://doi.org/10.2136/sssabookser5.4.c9>
- Haider M, Nafees M, Iqbal R (2024) Rejuvenating potato growth and yield in challenging semiarid and saline sandy cholistan: harnessing pgpb-coated n and p application strategies. *BMC Plant Biol* 24(1). <https://doi.org/10.1186/s12870-024-05056-x>
- Hajihashemi S, Mbarki S, Skalicky M (2020) Effect of wastewater irrigation on photosynthesis, growth, and anatomical features of two wheat cultivars (*Triticum aestivum* L.). *Water* 12(2):607. <https://doi.org/10.3390/w12020607>
- Hasan A, Tabassum B, Hashim M (2024) Role of plant growth promoting rhizobacteria (PGPR) as a plant growth enhancer for sustainable agriculture: A review. *Bacteria* 3(2):59–75. <https://doi.org/10.3390/bacteria3020005>
- Hashem MS, Qi X (2021) Treated wastewater irrigation—A review. *Water* 13(11):1527. <https://doi.org/10.3390/w13111527>
- Howell TA (2001) Enhancing water use efficiency in irrigated agriculture. *Agron J* 93:281–289
- Ijaz M, Sarfraz M, Nawaz A et al (2018) Diluted sugar mill effluent application with PGPR improves the performance of maize (*Zea Mays* L.) under an arid climate. *Agronomy* 8(5):67. <https://doi.org/10.3390/agronomy8050067>
- Ilangumaran G, Smith DL (2017) Plant growth promoting rhizobacteria in amelioration of salinity stress: a systems biology perspective. *Front Plant Sci* 8:1768. <https://doi.org/10.3389/fpls.2017.01768>
- Istanbuluoglu A (2009) Effects of irrigation regimes on yield and water productivity of safflower (*Carthamus tinctorius* L.) under mediterranean Climatic conditions. *Agric Water Manage* 96(12):1792–1798
- Istanbuluoglu A, Gocmen E, Gezer E, Pasa C (2009) Effects of water stress at different development stages on yield and water productivity of winter and summer safflower (*Carthamus tinctorius* L.). *Agric Water Manage* 96(10):1429–1434
- Kanber R, Ünlü M (2010) Water and soil salinity in agriculture, Cukurova university. A-87, Adana, Book No
- Kar G, Kumar A, Martha M (2007) Water use efficiency and crop coefficients of dry season oilseed crops. *Agric Water Manage* 87:73–82
- Kermani M, Asadi M (2018) Technical and economic evaluation of the deficit irrigation on yield of cotton. International Association of Agricultural Economists (IAAE) 2018 Conference Vancouver, British Columbia
- Khademian R, Ghassemi S, Asghari B (2019) Bio-fertilizer improves physio-biochemical characteristics and grain yield of safflower (*Carthamus tinctorius* L.) under drought stress. *Russian Agricultural Sci* 45:458–463. <https://doi.org/10.3103/S1068367419050124>
- Khalifa A, Alsyeed A, Almalki M (2016) Characterization of the plant growth promoting bacterium, *Enterobacter cloacae* msr1, isolated from roots of non-nodulating medicago sativa. *Saudi J Biol Sci* 23(1):79–86. <https://doi.org/10.1016/j.sjbs.2015.06.008>
- Khan N, Bano A (2016) Modulation of phytoremediation and plant growth by the treatment with PGPR, ag nanoparticle and untreated municipal wastewater. *Int J Phytoremediation* 18(12):1258–1269. <https://doi.org/10.1080/15226514.2016.1203287>
- Khan N, Ali S, Tariq H (2020) Water conservation and plant survival strategies of rhizobacteria under drought stress. *Agronomy* 10(11):1683. <https://doi.org/10.3390/agronomy10111683>
- Khoshru B, Mitra D, Khoshmanzar E (2020) Current scenario and future prospects of plant growth-promoting rhizobacteria: an economic valuable resource for the agriculture revival under stressful conditions. *J Plant Nutr* 43(20):3062–3092. <https://doi.org/10.1080/01904167.2020.1799004>
- Kotan R, Mohammadi P, Karagoz K (2014) Determination of broad spectrum bacterial strains which can be used as biopesticides and biofertilizers in agriculture. Turkey V. Plant Protection Symposium 3(5):313
- Kuan KB, Othman R, Abdul Rahim K et al (2016) Plant growth-promoting rhizobacteria inoculation to enhance vegetative growth, nitrogen fixation and nitrogen remobilisation of maize under greenhouse conditions. *PLoS ONE* 11(3):e0152478. <https://doi.org/10.1371/journal.pone.0152478>
- Kuşçu H, Turhan A, Özmen N et al (2015) Effects of different irrigation regimes on water use efficiency, yield and fruit quality of watermelon under bursa ecological conditions. *J Fac Agric Akdeniz Univ* 28(1):21–26
- Kuslu Y, Sahin U, Kiziloglu FM et al (2014) Fruit yield and quality, and irrigation water use efficiency of summer squash drip-irrigated with different irrigation quantities in a semi-arid agricultural area. *J Integr Agric* 13(11):2518–2526
- Lack S, Ghoshchi F, Hadi H (2013) The effect of crop growth enhancer bacteria on yield and yield components of safflower (*Carthamus tinctorius* L.). *Int J Farm Alli Sci* 2(20):809–815
- Lahlou FZ, Mackey HR, Al-Ansari T (2021) Wastewater reuse for livestock feed irrigation as a sustainable practice: A socio-environmental-economic review. *J Clean Prod* 294:126331. <https://doi.org/10.1016/j.jclepro.2021.126331>
- Lerna A, Mauromicale G (2020) How moderate water stress can affect water use efficiency indices in potato. *Agronomy* 10(7):1034. <https://doi.org/10.3390/agronomy10071034>
- Li HB, Singh RK, Singh P et al (2017) Genetic diversity of nitrogen-fixing and plant growth promoting *Pseudomonas* species isolated from sugarcane rhizosphere. *Front Microbiol* 8:1268. <https://doi.org/10.3389/fmicb.2017.01268>
- Li X, Zhang H, Li F et al (2022) Evaluating effects of regulated deficit irrigation under mulched on yield and quality of pumpkin in a cold and arid climate. *Water* 14(10):1563. <https://doi.org/10.3390/w14101563>

- Loeppert RH, Suarez DL (1996) Carbonate and Gypsum. Methods of Soil Analysis. <https://doi.org/10.2136/sssabookser5.3.c15>
- Lovelli S, Perniola M, Ferrara A et al (2007) Yield response factor to water (Ky) and water use efficiency of *Carthamus tinctorius* L. and *Solanum melongena* L. Agric. Water Manage 92:73–80. <https://doi.org/10.1016/j.agwat.2007.05.005>
- Lu Y, Song S, Wang R, Liu Z et al (2015) Impacts of soil and water pollution on food safety and health risks in China. Environ Int 77:5–15. <https://doi.org/10.1016/j.envint.2014.12.010>
- Karakaya Z, Ödemis B (2019) Determination of relationship water-yield of inoculated and uninoculated soybean in different irrigation water level. Mustafa Kemal University J Agric Sci 24:278–289.
- Mahjoub O, Mauffret A, Michel C et al (2022) Use of groundwater and reclaimed water for agricultural irrigation: farmers' practices and attitudes and related environmental and health risks. Chemosphere 295:133945. <https://doi.org/10.1016/j.chemosphere.2022.133945>
- Mahreen N, Yasmin S, Asif M, Yahya M et al (2023) Mitigation of water scarcity with sustained growth of rice by plant growth promoting bacteria. Front Plant Sci. <https://doi.org/10.3389/fpls.2023.1081537>
- Marsic NK, Sturm M, Zupanc V et al (2012) Quality of white cabbage yield and potential risk of ground water nitrogen pollution, as affected by nitrogen fertilisation and irrigation practices. J Sci Food Agric 92(1):92–98. <https://doi.org/10.1002/jsfa.4546>
- Mondani F, Khani K, Honarmand SJ et al (2019) Evaluating effects of plant growth-promoting rhizobacteria on the radiation use efficiency and yield of soybean (*Glycine max*) under water deficit stress condition. Agric Water Manage 213:707–713. <https://doi.org/10.1016/j.agwat.2018.11.004>
- Moradi L, Ehsanzadeh P (2015) Effects of cd on photosynthesis and growth of safflower (*Carthamus tinctorius* L.) genotypes. Photosynthetica 53:506–518. <https://doi.org/10.1007/s11099-015-0150-1>
- Mousavi SR, Shahsavari M (2014) Effects of treated municipal wastewater on growth and yield of maize (*Zea mays*). Biol Forum 6(2):228–233
- Mutai C, Njuguna J, Ghimire S (2017) Brachiaria grasses (*brachiaria spp.*) harbor a diverse bacterial community with multiple attributes beneficial to plant growth and development. Microbiolgyopen 6(5). <https://doi.org/10.1002/mbo3.497>
- Nelson DW, Sommers LE (1996) Total carbon, organic carbon, and organic matter. Methods of Soil Analysis. <https://doi.org/10.2136/sssabookser5.3.c34>
- Nemera DB, Bar-Tal A, Levy GJ et al (2021) Mitigating negative effects of long-term treated wastewater irrigation: leaf gas exchange and water use efficiency response of avocado trees (*Persea Americana* Mill). Agric Water Manage 256:107126. <https://doi.org/10.1016/j.agwat.2021.107126>
- Ors S, Ekinici M, Yildirim E et al (2016) Changes in gas exchange capacity and selected physiological properties of squash seedlings (*Cucurbita Pepo* L.) under well-watered and drought stress conditions. Arch Agron Soil Sci 62(12):1700–1710. <https://doi.org/10.1080/03650340.2016.1168517>
- Quemada M, Delgado A, Mateos L (2016) Nitrogen fertilization I: the nitrogen balance. In: Villalobos, F.J., Fereres, E. (Eds.), Principles of Agronomy for Sustainable Agriculture. Springer International Publishing AG Chapter 24. https://doi.org/10.1007/978-3-319-46116-8_24
- Nzediegwu C, Prasher S, Elsayed E (2019) Effect of Biochar on the yield of potatoes cultivated under wastewater irrigation for two seasons. J Soil Sci Plant Nutr 19:865–877. <https://doi.org/10.1007/s42729-019-00085-0>
- Oskay V, Karagöz Ö, Kuşlu S (2023) Investigation of the water quality of Aktutan pond located in Gümüşhane Province in the North East region of Turkey by Hazen statistical method. Environ Earth Sci 82:118. <https://doi.org/10.1007/s12665-023-10799-1>
- Ozer H, Coban F, Sahin U et al (2020) Response of black Cumin (*Nigella sativa* L.) to deficit irrigation in a semi-arid region: Growth, yield, quality, and water productivity. Ind Crops Prod 144:112048. <https://doi.org/10.1016/j.indcrop.2019.112048>
- Paul D, Lade H (2014) Plant-growth-promoting rhizobacteria to improve crop growth in saline soils: a review. Agron Sustain Dev 34(4):737–752. <https://doi.org/10.1007/s13593-014-0233-6>
- Pejić B, Maksimović L, Škorić D et al (2009) Effect of water stress on yield and evapotranspiration of sunflower/Efecto Del estrés hídrico sobre El Rinde y apotranspiración de girasol/Effet du stress hydrique Sur Le rendement et l'évapotranspiration du tournesol. Helia 32(51):19–32. <https://doi.org/10.2298/HEL0951019P>
- Perulli GD, Gaggia F, Sorrenti G et al (2021) Treated wastewater as irrigation source: A Microbiological and chemical evaluation in Apple and nectarine trees. Agric Water Manage 244:106403. <https://doi.org/10.1016/j.agwat.2020.106403>
- Rady MO, Semida WM, Howladar SM et al (2021) Raised beds modulate physiological responses, yield and water use efficiency of wheat (*Triticum aestivum* L) under deficit irrigation. Agric Water Manage 245:106629. <https://doi.org/10.1016/j.agwat.2020.106629>
- Rao SS, Tanwar SPS, Regar PL (2016) Effect of deficit irrigation, phosphorous inoculation and Cycocel spray on root growth: seed cotton yield and water productivity of drip irrigated cotton in arid environment. Agric Water Manage 169:14–25. <https://doi.org/10.1016/j.agwat.2016.02.008>
- Rawashdeh HM (2017) Sunflower seed yield under trickle irrigation using treated wastewater. Afr J Agric Res 12(21):1811–1816. <https://doi.org/10.5897/AJAR2017.12208>
- Řezanka T, Palyzová A, Sigler K (2018) Isolation and identification of siderophores produced by cyanobacteria. Folia Microbiol 63(5):569–579. <https://doi.org/10.1007/s12223-018-0626-z>
- Rhoades JD (1996) Salinity: electrical conductivity and total dissolved solids. Methods of Soil Analysis 5:417–435
- Riaz U, Murtaza G, Anum W et al (2020) Plant growth-promoting rhizobacteria (PGPR) as biofertilizers and biopesticides. Microbiota and biofertilizers: a sustainable continuum for plant and soil health. Springer International Publishing, Cham, pp 181–196. https://doi.org/10.1007/978-3-030-48771-3_11
- Saad AM, Elhabbak AK, Abbas MH et al (2023) Can deficit irrigations be an optimum solution for increasing water productivity under arid conditions? A case study on wheat plants. Saudi J Biol Sci 30(2):103537. <https://doi.org/10.1016/j.sjbs.2022.103537>
- Saeidi M, Yaghoob R, Amini R, Taghizadeh A (2018) Changes in fatty acid and protein of safflower as response to biofertilizers and cropping system. Turkish J Field Crops 23(2):117–126. <https://doi.org/10.17557/tjfc.471666>
- Safi-naz SZ, Shaaban MM (2015) Impact of treated sewage water irrigation on some growth parameters, yield and chemical composition of sunflower plants. Int J ChemTech Res 8:114–122
- Sahin U, Ekinici M, Kiziloglu FM et al (2015) Ameliorative effects of plant growth promoting bacteria on water-yield relationships, growth, and nutrient uptake of lettuce plants under different irrigation levels. HortScience 50(9):1379–1386. <https://doi.org/10.21273/HORTSCI.50.9.1379>
- Samancioglu A, Yildirim E, Sahin Ü (2016) Effect of seedlings Development, some physiological and biochemical properties of cabbage seedlings grown at different irrigation levels of the plant growth promoting rhizobacteria application. KSÜ J Agric Nat 19(3):332–338
- Santos A, Silveira J, Bonifácio A et al (2018) Antioxidant response of Cowpea co-inoculated with plant growth-promoting bacteria

- under salt stress. *Brazilian J Microbiol* 49(3):513–521. <https://doi.org/10.1016/j.bjm.2017.12.003>
- Sarathambal C, Thangaraju M, Paulraj C et al (2010) Assessing the zinc solubilization ability of *Gluconacetobacter diazotrophicus* in maize rhizosphere using labelled 65 Zn compounds. *Indian J Microbiol* 50:103–109. <https://doi.org/10.1007/s12088-010-0066-1>
- Sarawaneeyaruk S, Lorliam W, Krajangsang S (2019) Enhancing plant growth under municipal wastewater irrigation by plant growth promoting rhizospheric *Bacillus* spp. *J King Saud University-Science* 31(3):384–389. <https://doi.org/10.1016/j.jksus.2018.04.027>
- Schilling J, Hertig E, Trambly Y (2020) Climate change vulnerability, water resources and social implications in North Africa. *Reg Environ Chang* 20:1–12. <https://doi.org/10.1007/s10113-020-01597-7>
- Sengupta S, Nawaz T, Beaudry J (2015) Nitrogen and phosphorus recovery from wastewater. *Curr Pollution Rep* 1(3):155–166. <http://doi.org/10.1007/s40726-015-0013-1>
- Sezen SM, Yucel S, Tekin S et al (2019a) Determination of optimum irrigation and effect of deficit irrigation strategies on yield and disease rate of peanut irrigated with drip system in Eastern mediterranean. *Agric Water Manage* 221:211–219. <https://doi.org/10.1016/j.agwat.2019.04.033>
- Sezen SM, Yazar A, Tekin S (2019b) Physiological response of red pepper to different irrigation regimes under drip irrigation in the mediterranean region of Turkey. *Sci Hort* 245:280–288. <https://doi.org/10.1016/j.scienta.2018.10.037>
- Shah A, Nazari M, Antar M (2021) PGPR in agriculture: A sustainable approach to increasing climate change resilience. *Front Sustainable Food Syst* 5:667546. <https://doi.org/10.3389/fsufs.2021.667546>
- Shah P, Abid M, Kousar Yasmeen TN (2022) Quality measurements of various types of wastewaters and their impacts on plant growth. *Pak J Bot* 54(2):629–637. <https://doi.org/10.30848/PJB2022>
- Shahrokhnia MH, Sepaskhah AR (2017) Physiologic and agronomic traits in safflower under various irrigation strategies, planting methods and nitrogen fertilization. *Ind Crops Prod* 95:126–139. <https://doi.org/10.1016/j.indcrop.2016.10.021>
- Shareef M, Gui D, Zeng F, Waqas M et al (2018) Water productivity, growth, and physiological assessment of deficit irrigated cotton on hyperarid desert-oases in Northwest China. *Agric Water Manage* 206:1–10. <https://doi.org/10.1016/j.agwat.2018.04.042>
- Silva ER, Zoz J, Oliveira CES et al (2019a) Can co-inoculation of Bradyrhizobium and azospirillum alleviate adverse effects of drought stress on soybean (*Glycine max* L. Merrill)? *Arch Microbiol* 201(3):325–335. <https://doi.org/10.1007/s00203-018-01617-5>
- Silva JAD, Rezende MK, Flumignan DL (2019b) Yield response factor (ky) for winter corn crop in the region of dourados, MS, Brazil. *Engenharia Agricola* 39(5):573–578. <https://doi.org/10.1590/1809-4430-Eng.Agric.v39n5p573-578/2019>
- Singh S (2016) Water stress physiology and crop modeling of spring safflower under different irrigation management strategies. New Mexico State University
- Singh D, Yadav DK, Fatima F (2020) Characterization and genetic diversity of *Pantoea agglomerans* isolates having dual potentiality to suppress growth of *Ralstonia solanacearum* and plant growth promoting ability. *Indian Phytopathol* 73(4):643–653. <https://doi.org/10.1007/s42360-020-00268-1>
- Smith M, Steduto P (2012) Yield response to water: the original FAO water production function, 6–13
- Soltani H, Hassani A, Sari MBA, Hanifei M (2025) The phosphate solubilizing and N fixing *Pantoea agglomerans* bacteria affecting yield and biochemical properties including nutrient uptake of different tomato genotypes. *J Trace Elem Minerals* 12:100225. <https://doi.org/10.1016/j.jtemin.2025.100225>
- Sood G, Kaushal R, Sharma M (2020) Alleviation of drought stress in maize (*Zea Mays* L.) by using endogenous endophyte *Bacillus subtilis* in North West Himalayas. *Acta Agric Scand Sect B Soil Plant Sci* 70:361–370. <https://doi.org/10.1080/09064710.2020.1743749>
- Stępień A, Wojtkowiak K, Kolankowska E (2022) Effect of commercial microbial preparations containing *Paenibacillus azotofixans*, *Bacillus megaterium* and *Bacillus subtilis* on the yield and photosynthesis of winter wheat and the nitrogen and phosphorus content in the soil. *Appl Sci* 12(24):12541. <https://doi.org/10.3390/app122412541>
- Swarnalakshmi K, Yadav V, Tyagi D et al (2020) Significance of plant growth promoting rhizobacteria in grain legumes: growth promotion and crop production. *Plants* 9(11):1596. <https://doi.org/10.3390/plants9111596>
- Tanveer S, Ali B (2022) Evaluation of *Bacillus* and rhizobium strains to enhance the growth of *Vigna radiata* (L.) under drought stress. *Pak-Euro J Med Life Sci* 5(1):101–112. <https://doi.org/10.31580/pjmls.v5i1.2433>
- Thomas GW (1996) Soil pH and Soil acidity. In *Methods of Soil Analysis*. <https://doi.org/10.2136/sssabookser5.3.c16>
- Torabi B, Adibniya M, Rahimi A (2015) Seedling emergence response to temperature in safflower: measurements and modeling. *Int J Plant Prod* 9(3):393–412
- Turan M, Ekinci M, Yildirim E et al (2014) Plant growth-promoting rhizobacteria improved growth, nutrient, and hormone content of cabbage (*Brassica oleracea*) seedlings. *Turkish J Agric Forestry* 38(3):327–333. <https://doi.org/10.3906/tar-1308-62>
- Tutar H (2024) Bioethanol yield of the sorghum × Sudangrass hybrid under arid and semiarid conditions: nitrogen dose effects, orthogonal comparisons, and component analyses. *Turkish J Agric Forestry* 48(6):1070–1083. <https://doi.org/10.55730/1300-011X.3242>
- Ulloa-Ogaz AL, Muñoz-Castellanos LN, Nevárez-Moorillón GV (2015) Biocontrol of phytopathogens: antibiotic production as mechanism of control. The battle against microbial pathogens: basic science. *Technological Adv Educational Programs* 1:305–309
- Vejan P, Abdullah R, Khadiran T, Ismail S et al (2016) Role of plant growth promoting rhizobacteria in agricultural sustainability—a review. *Molecules* 21(5):573. <https://doi.org/10.3390/molecules21050573>
- Vergine P, Salerno C, Libutti A et al (2017) Closing the water cycle in the agro-industrial sector by reusing treated wastewater for irrigation. *J Clean Prod* 164:587–596. <https://doi.org/10.1016/j.jclepro.2017.06.239>
- Wu WY, Lo MH, Wada Y et al (2020) Divergent effects of climate change on future groundwater availability in key mid-latitude aquifers. *Nat Commun* 11(1):3710. <https://doi.org/10.1038/s41467-020-17581-y>
- Yang J, Jia R, Gao Y et al (2017) The reliability evaluation of reclaimed water reused in power plant project. *IOP Conf Series: Earth Environ Sci* 100:012189
- Yang F, Jiang H, Ma K et al (2024) Genomic and phenotypic analyses reveal *paenibacillus polymyxa* pjh16 is a potential biocontrol agent against cucumber fusarium wilt. *Front Microbiol*. <https://doi.org/10.3389/fmicb.2024.1359263>
- Yavuz D, Seymen M, Süheri S et al (2020) How do rootstocks of Citron watermelon (*Citrullus lanatus* var. citroides) affect the yield and quality of watermelon under deficit irrigation? *Agric Water Manage* 241:106351. <https://doi.org/10.1016/j.agwat.2020.106351>
- Yazdani AA, Saffari M, Ranjbar GH (2018) Application of treated wastewater on yield and heavy metals content of seeds in sunflower cultivars. *Aust J Crop Sci* 12(5):731–737

- Yazdani AA, Saffari M, Ranjbar G (2019) Effect of application of treated wastewater on seed yield and heavy metals content of safflower cultivars. *J Agricultural Sci Technol* 21(5):1277–1286
- Yeloojeh KA, Saeidi G, Sabzalian MR (2020) Drought stress improves the composition of secondary metabolites in safflower flower at the expense of reduction in seed yield and oil content. *Ind Crops Prod* 154:112496. <https://doi.org/10.1016/j.indcrop.2020.112496>
- Yildirim E, Ekinci M, Sahin U, Ors S et al (2021) Improved water productivity in summer squash under water deficit with PGPR and synthetic Methyl amine applications. *Rhizosphere* 20:100446. <https://doi.org/10.1016/j.rhisph.2021.100446>
- Yu L, Gao X, Zhao X (2020) Global synthesis of the impact of droughts on crops' water-use efficiency (WUE): towards both high WUE and productivity. *Agric Syst* 177:102723. <https://doi.org/10.1016/j.agry.2019.102723>
- Zarei T (2022) Balancing water deficit stress with plant growth-promoting rhizobacteria: A case study in maize. *Rhizosphere* 100621. <https://doi.org/10.1016/j.rhisph.2022.100621>
- Zarei T, Moradi A, Kazemeini SA et al (2019) Improving sweet corn (*Zea Mays* L. var *saccharata*) growth and yield using *Pseudomonas fluorescens* inoculation under varied watering regimes. *Agric Water Manag* 226:105757. <https://doi.org/10.1016/j.agwat.2019.105757>
- Zou Y, Saddique Q, Ali A et al (2021) Deficit irrigation improves maize yield and water use efficiency in a semi-arid environment. *Agric Water Manage* 243:106483. <https://doi.org/10.1016/j.agwat.2020.106483>

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.