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Impact of Irrigation Water Salinity and Plant Growth Promoting Rhizobacteria on Some Soil Properties in Pot Experiment

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Abstract

Increasing use of saline water resources for irrigation of agricultural lands, especially in arid and semi-arid areas, in addition to the accumulation of salts in the soil, has caused the loss of various properties of the soil and reduced the yield of agricultural products. Plant growth promoting rhizobacteria (PGPR) by producing different compounds can improve soil properties and reduce the negative effects of salinity stress on soil and plants function. In this study, the effect of PGPR [Control ($PGPR_0$), *Pseudomonas sp.* 1 ($PGPR_1$) and *Pseudomonas sp.* 2 ($PGPR_2$)] and different levels of irrigation water salinity (0, 5 and 10 $dS.m^{-1}$) on some soil properties in the rhizosphere of pistachio seedlings was investigated. The results showed that with the increase in irrigation water salinity, the amount of electrical conductivity (EC), soluble forms of sodium (Na_s) and magnesium (Mg_s), sodium absorption ratio (SAR), HCO_3 and soil moisture content (Θ_m) increased by 3.8 times, 5.2 times, 2.5 times, 2.3 times, 23% and 59%, respectively, but the amount of pH, available phosphorus (AP) and organic matter (OM) decreased by 2%, 25% and 20%, respectively. However, treatment with PGPRs increased the content of AP (35-78%), available potassium (10-18%), OM (18-29%) and Θ_m (48%) and decreased the content of Na_s (12-14%), ECe (10-12%), pH (3%) and SAR (14%) in different irrigation water salinity levels. Regarding to the presented result, using salt-tolerant bacteria in agricultural lands with saline water and soil can mitigate the negative effects of salinity stress on soil properties.

Keywords: Nutrient availability, Rhizobacteria, Soil physiochemical properties, Soil reclamation, Water quality.

1. Introduction

Fresh water resources have played an essential role in the production of agricultural products and its lack has limited the development of many countries in the world (Wang et al., 2020). The scarcity of fresh water resources for agriculture is more evident in Iran as an arid/semi-arid country. Currently, about 55.3 billion cubic meters of net water are used as evapotranspiration in Iran's land for agricultural production (Khorsandi et al., 2022). On the other hand, despite the decrease in water availability in Iran due to the effects of climate change (such as increased temperature and evaporation and decreased precipitation), the irrigated agricultural lands have developed during the last decades (Rafiei-Sardooi et al., 2022). In addition to serious geological and environmental effects such as land subsidence (Han et al., 2021), one of the most important results of the unsustainable agricultural development and water consumption in Iran is the decrease in the quantity and quality of underground water (Noori et al., 2023). Therefore, cultivation of agricultural lands using unconventional water resources, including saline water, is necessary to face overpopulation worldwide (Amin, 2023).

Saline and brackish waters is used to irrigate agricultural lands in various parts of the world, particularly in arid and semi-arid regions, which occupy about 41% of the global earth's surface and are faced with limited quality water resources (Huang et al., 2011). In arid and semi-arid regions, due to the insufficient amount of precipitation to leach out the salts from the soil profile, salts accumulate from the saline irrigation water in the root zone of plants and affect the physicochemical properties of the soil (Pessoa et al., 2019). However, irrigation with saline water may lead to the accumulation of salt in the soil profile, resulting in varying degrees of soil salinization and alkalization. One of the effects of salt accumulation in the soil tillage layer is the reduction of fertility and availability of nutrients for plants. In addition to threatening environmental resources and human health, salinity stress reduces crop yield and restricts the use of agricultural land. The salinity (NaCl or Na_2SO_4) stress effects are typically ionic and osmotic (Guo et al., 2021). Irrigation water with high salt ions content could decrease the soil nutrients availability and negatively influence the growth and activity of soil microorganisms (Singh et al., 2021). Irrigation with saline water not only stimulates the salinization and alkalization process in soil, but also alters activity and diversity of soil microorganisms, enzymes activity, nitrogen availability, and nitrification and denitrification processes (Irshad et al., 2005). Hu et al. (2020) reported that irrigation with saline water increased soil sodium adsorption ratio (SAR) and electrical conductivity (EC), and reduced organic carbon content of soil. The variations in the physicochemical properties of the soil caused by saline water irrigation will influence the plants growth and development, ultimately influencing the yield of the crop (Wang et al., 2016). Although the use of saline water sources for agriculture is unavoidable, but to reduce the negative effects of irrigation water salinity stress on soil and plant properties, it is necessary to use different management methods.

The use of salt tolerant plant growth promoting rhizobacteria (PGPR) is one of the modern approaches to improve the properties of saline soils as well as increase plant tolerance to salt stress (Egamberdieva and Kucharova, 2009). Also, these rhizobacteria have shown their ability in promoting plant growth and yields in arid and semiarid area (Niu et al., 2018). Beneficial soil microorganisms play a vital role in the cycle of organic matter and the availability of nutrients in the soil and regulate various ecological processes related to the growth of plants in the soil (Tang et al., 2023). PGPR show high adaptability to different environments due to their fast growth rate, the ability to metabolize various organic compounds in the soil and high biochemical diversity. These rhizobacteria can also improve soil properties and plant growth by producing organic acids, phytohormones, cyanide hydrogen (HCN), siderophores, auxins and 1-aminocyclopropane-1-carboxylate (ACC) deaminase, especially in stressful conditions (Azarmi-Atajan and Sayyari Zahan, 2020). On the other hand, some soil rhizobacteria such as Pseudomonas can synthesize exo-polysaccharide, which plays an important role in improving the soil structure and thus enhances soil permeability. This compound can have a positive effect on retaining more water in the soil and ultimately maintain plant growth under water stress (Alaskar and Al-Shwaiman, 2023). Li et al (2020) indicated that the use of PGPR inoculants increased soil available nitrogen, available phosphorus, available potassium, organic carbon and various enzymes activity in the rhizosphere of *A. sativa*, *M. sativa*, and *C. sativus.* Similarly, inoculation with PGPR significantly increased the concentration of soil available N, P, and K as well as soil urease, sucrase, dehydrogenase and protease activities in the alfalfa rhizosphere (Tang et al., 2023).

Therefore, considering the increase in salinity of irrigation water sources, especially in pistachio farming areas of Iran, the aim of this study is to investigate the effect of different levels of irrigation water salinity and PGPR on some soil properties in the rhizosphere of pistachio seedlings under greenhouse conditions.

2. Materials and Methods

2.1. Experimental design

In order to investigate the effect of different levels of irrigation water salinity and PGPR on some soil properties in the rhizosphere of pistachio seedlings, a factorial experiment was conducted in the form of a completely randomized design in greenhouse conditions with three replications. The experimental treatments included PGPR at three levels

[Control ($PGPR_0$), *Pseudomonas sp.* 1 ($PGPR_1$) and *Pseudomonas sp.* 2 ($PGPR_2$)] and irrigation water salinity at three levels (0, 5 and 10 $dS.m^{-1}$). For this study, two Pseudomonas genus bacteria with high plant growth activities (including the production of auxin and siderophore and dissolution of tricalcium phosphate), and high tolerance to salinity stress in laboratory conditions were selected. To prepare the microbial inoculum, after culturing rhizobacteria on the King's B medium, they were grown on a Nutrient Broth (NB) medium in a shaker at 25 ºC for 48 hours. Also, saline water sources for irrigation were prepared using Sodium Chloride (NaCl) salt. An agricultural soil sample with low electrical conductivity (EC) was selected and after air drying, it was pounded and passed through sieve 4-mm to remove stones and mixed thoroughly. Then some physical and chemical properties of the soil (Table 1) were measured (Sparks, 1996). After filling the pots with 2 kg of prepared soil, 5 germinated pistachios (*P. vera* L. cv. Badami) seeds were planted in each pot. Then, each pistachio seed was treated with bacterial suspension (500 µL for each seed with CFU[1] $=10^8$ $cell.mL^{-1}$). Finally, 2 seedlings were kept in each pot and watered with distilled water for one month. Irrigation with saline water started 30 days after planting, and the crop was irrigated until the end of the growth period (4 month) to maintain the soil at field capacity.

Table 1. Selected the soil physicochemical properties used in the experiment

Texture	pH	ECe	OM	SP	P_{av}	K_{av}	Na_s	Ca_s	Mg_s	SAR
		($dS.m^{-1}$)	%	%	($mg.kg^{-1}$)		($mEq.L^{-1}$)			$(mEq.L^{-1})^{0.5}$
Sandy Loam	7.70	1.40	0.57	30	7.12	179	7.30	5.60	7.58	2.85

2.2. Rhizosphere soil properties analysis

After the growth period, the seedlings were cut from the soil surface and their roots were slowly removed from the soil. Finally, the soil attached to the roots is considered as rhizospheric soil and various properties, including electrical conductivity (ECe) by the method of Rhoades (1996), reaction (pH) by the method of Richards (1954), available potassium (AK) by the method of Page et al. (1982), available phosphorus (AP) by the method of Olsen et al. (1954), organic carbon (OC) by the method of Walkey and Black (1934), soluble sodium (Na), calcium (Ca), magnesium (Mg) and bicarbonate (HCO_3^-) by the method of Sparks (1996) were measured in the rhizospheric soil. Soil moisture content (Θ_m) was measured 7 days after the last watering in the pots. Sodium absorption ratio (SAR) was also calculated using the following equation (1):

$$SAR = \frac{Na^+}{\sqrt{\frac{Ca^{2+} + Mg^{2+}}{2}}} \tag{1}$$

The units of Ca^{2+}, Mg^{2+} and Na^+ are mill equivalent/liter ($meq.L^{-1}$).

2.3. Statistical analysis

The recorded data were analyzed according to ANOVA procedures and means were separated by least significant difference (LSD) at 5% level of significance using the SAS software.

3. Results and Discussion

3.1. Soil reaction (pH) and electrical conductivity (ECe)

The analysis of variance illustrated that only the main effects of PGPRs and irrigation water salinity on the rhizosphere soil reaction (pH) was significant ($p \leq 0.05$). Also, the electrical conductivity of rhizosphere soil was significantly influenced ($p \leq 0.05$) by the PGPRs, irrigation water salinity and PGPRs × irrigation water salinity interaction (Table 2).

According to the results, inoculation with rhizobacteria reduced the rhizosphere soil pH value. However, this reduction was significant only for $PGPR_2$ isolate. Inoculation with $PGPR_2$ significantly decreased the rhizosphere soil pH value from 7.53 to 7.32 (Fig. 1a). Generally, the production of auxins, such as IAA, by PGPRs can promote the root growth of plants and thus increase root secretions such as organic acids and protons and thus reduce rhizosphere pH (Selvakumar et al., 2012).

[1] Colony Forming Unit

This decrease in soil pH increases the concentration of nutrients in the rhizosphere, including P, K and micronutrients. Also, with increasing irrigation water salinity levels, pH value of rhizosphere soil reduced. The value of pH in the rhizosphere of pistachio seedlings irrigated with 5 $dS.m^{-1}$ water salinity level significantly decreased from 7.51 to 7.35 (Fig. 1b).

Table 2. Analysis of variance (mean of square) for measured traits

SOV	df	ECe	pH	OM	AP	AK	Θ_m	Na_s	Ca_s	Mg_s	Ca/Mg	SAR	HCO_3
PGPR (P)	2	0.218^{ns}	0.102^{**}	0.050^{**}	29.5^{**}	1136^{**}	9.15^{ns}	3734^{ns}	186^{ns}	119^{ns}	0.407^{**}	0.204^{ns}	7.00^{ns}
Water Salinity (S)	2	37.0^{**}	0.060^{*}	0.049^{**}	6.41^{**}	3240^{**}	67.1^{**}	518018^{**}	383585^{**}	7171^{**}	18.4^{**}	25.6^{**}	613^{**}
P × S	4	0.378^{*}	0.005^{ns}	0.0003^{ns}	1.16^{*}	274^{*}	15.1^{*}	7182^{*}	4212^{*}	336^{*}	0.367^{**}	0.686^{**}	78.7^{ns}
Error	18	0.124	0.016	0.005	0.345	86.0	3.44	2271	1256	100	0.061	0.144	69.9
CV (%)		9.90	1.73	11.1	8.21	5.39	10.0	11.3	12.2	11.4	8.19	7.02	11.4

**, * and ns: significant at $p \leq 0.01$, significant at $p \leq 0.05$ and non-significant, respectively.

Irrigation with saline water- especially with a high amount of Na- can replace H^+ ions with Na^+ and thus reduce the pH of the soil (Van Tan and Thanh, 2021). The results showed that the application of irrigation water salinity levels of 5 and 10 $dS.m^{-1}$ significantly increased soil ECe from 1.67 to 3.11 and 6.31 $dS.m^{-1}$, respectively (Table 3). Usually, increasing the salinity of the irrigation water also increases the salinity of the soil. Although the intensity and amount of this increase is different according to irrigation management and methods. The increase in soil salinity can be related to the absorption of soluble and exchangeable cations from saline water by soil particles with a high specific surface area (Cucci et al., 2013). According to studies, irrigation with saline water increases the salinity of the saturated soil extract at the end of the growing season. Also, with the increase of the depth of the soil, the amount of salinity of the saturated soil extract increases (Kahlown and Azam, 2003). The increase in soil salinity due to irrigation with saline water was also reported by Wang et al (2023). However, although the use of rhizobacteria at irrigation water salinity levels of 0 and 5 $dS.m^{-1}$ did not have a significant effect on the rhizosphere soil ECe, but inoculation with both isolates caused a significant decrease in the rhizosphere soil ECe at 10 $dS.m^{-1}$ irrigation water salinity level. Treatment of seedlings with $PGPR_1$ and $PGPR_2$ isolates at 10 $dS.m^{-1}$ irrigation water salinity level significantly reduced the ECe of rhizosphere soil by 10 and 13%, respectively in comparison with the same salinity levels (Table 3). PGPR can reduce negative effects of salinity by production of 1-aminocyclopropane-1-carboxylate (ACC) deaminase enzyme, and cell wall-degrading enzymes ions, compatible solutes, as well as other secondary metabolites including phyto-hormones (Tiwari et al., 2022).

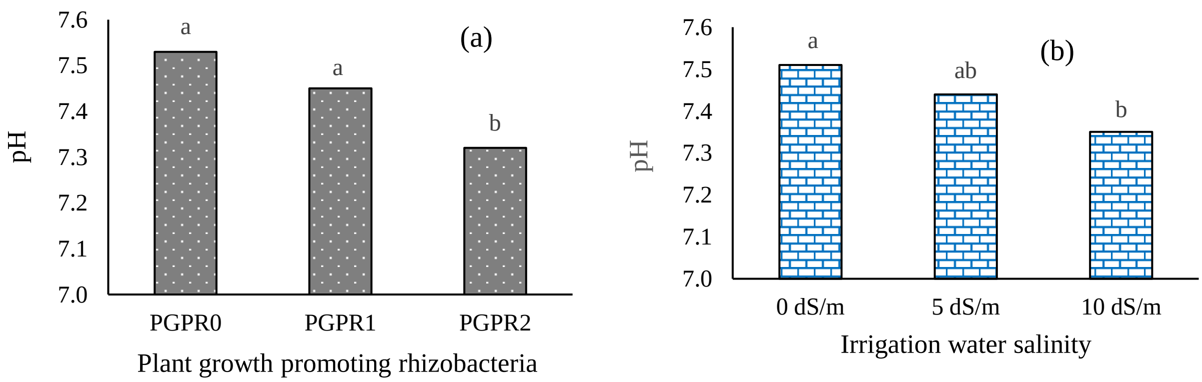

Fig. 1. Main effect of PGPR (a) and irrigation water salinity (b) on the rhizosphere soil reaction (pH). Within each graph, values followed by the same letter are not significantly different ($p \leq 0.05$) according to LSD test.

3.2. Organic matter (OM) content

The content of OM in rhizosphere soil was affected ($p \leq 0.01$) by simple effect of PGPRs inoculation and irrigation water salinity treatments (Table 2).

The results indicated that the application of rhizobacteria increased soil OM content in the rhizosphere soil. Inoculation of pistachio seedlings with $PGPR_1$ and $PGPR_2$ isolates significantly enhanced OM content in rhizosphere soil by 18 and 29%, respectively compared to the non-inoculated control (Fig. 2a). PGPRs play a vital role in the cycle of organic matter and the availability of nutrients in the soil and regulate various ecological processes related to the growth of plants in the soil (Tang et al., 2023). In addition to promoting plant growth, PGPRs can also improve the rhizosphere environment of the plant. Combined application of PGPR and rhizobium significantly increased soil total N, AP, soil organic matter contents and enzymatic activities compared with the control (Ju et al., 2019). Similarly, Li et al (2020) found that PGPR inoculation increased the concentration of EC, AN, AP, and soil organic carbon, AN and AP in the rhizosphere of *A. sativa*, *M. sativa*, and *C. sativus* seedlings. On the other hand, irrigation of seedlings with saline water caused a significant decrease in soil organic matter content. Based on the results, in comparison with the control, the content of soil OM decreased by 15 and 20% at the irrigation water salinity levels of 5 and 10 $dS.m^{-1}$, respectively (Fig. 2b). The reduction of soil organic matter in saline conditions can be attributed to the reduction of vegetation and the entry of plant material into the soil, as well as the increase in the rate of microbial decomposition due to the increase in the activity of carbon-decomposing enzymes (Morrissey et al., 2014). Wang et al. (2023) reported that the soil pH, saturated soil extract (EC_e) and SAR increased with the raise in salinity of irrigation water, whereas the organic carbon of soil and different enzymes activity decreased, which indicates that the use of saline water for irrigation has a negative effect on soil properties. Based on the results of Zhang et al. (2019b) studies, a negative correlation was observed between soil salinity and soil organic matter.

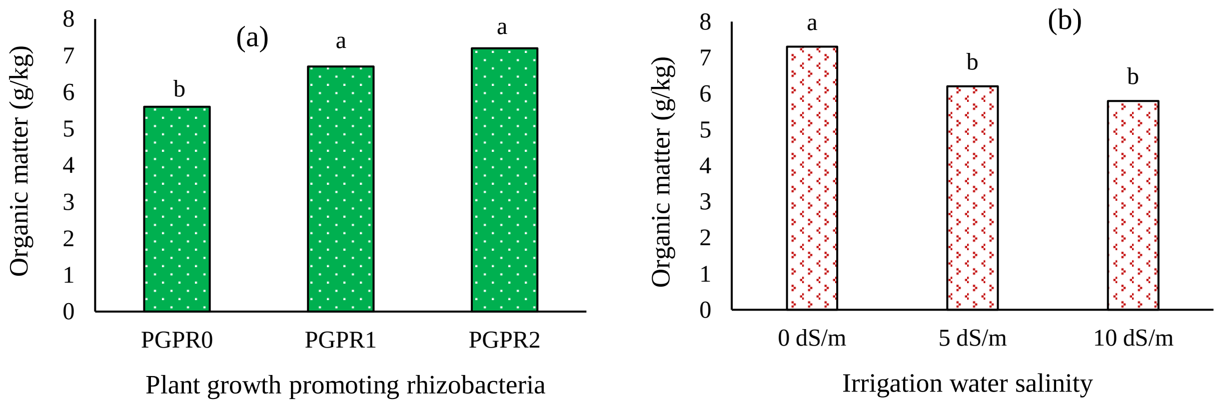

Fig. 2. Main effect of PGPR (a) and irrigation water salinity (b) on the rhizosphere soil organic matter content. Within each graph, values followed by the same letter are not significantly different ($p \leq 0.05$) according to LSD test.

3.3. Available phosphorus (AP) and available potassium (AK) content

The analysis of variance revealed that the main and interaction effect of PGPR and irrigation water salinity had a significant effect ($p \leq 0.05$) on the AP and AK content of rhizosphere soil (Table 2).

The results showed that the increase of irrigation water salinity to 10 $dS.m^{-1}$ reduced AP content by 26% in comparison with the control (Table 3). In saline soils, the availability of P is usually low because phosphate anions can be precipitated by reacting with Ca^{2+} and Mg^{2+} cations, which are abundant in saline water. Therefore, in addition to salt stress, plants grown in saline soils also face P deficiency (Penn and Camberato, 2019). Xie et al. (2022) also reported a negative correlation between salt content and available soil P. However, treatment with both PGPR isolates had a positive effect on AP content in both saline and non-saline conditions. Inoculation with $PGPR_1$ and $PGPR_2$ isolates significantly increased the rhizosphere soil AP content by 36 and 79% at 0 $dS.m^{-1}$ salinity level, by 43 and 49% at 5 dS.m^{-1} and by 66 and 78% at 10 dS.m^{-1} salinity level, respectively, relative to the same salinity levels. The highest amount of rhizosphere soil AP (10.3 mg.kg^{-1}) was related to the application of $PGPR_2$ at non-saline conditions and the lowest amount (4.28 mg.kg^{-1}) was related to the irrigation water salinity level 10 dS.m^{-1} (Table 3). Under saline conditions, the bioavailability of nutrients is low because salt alters the ion balance. However, salinity-tolerant bacteria are able to reduce some of the deleterious effects of salinity, improving plant growth, biomass accumulation, and yield (Etesami, 2020). The increase in the content of different nutrients such as N, P and K in the rhizosphere of the plant with the use of rhizobacteria has also been reported by Li et al (2020). Also, irrigation with saline water of 10 dS.m^{-1} significantly enhanced the amount of AK in the rhizosphere soil by 17% compared to the control. The use of saline water increases the concentration of solutes in the soil profile and the accumulation of ions in the soil. Accumulation of salts in the soil profile can reduce fertility and availability of nutrients for plants (Cucci et al., 2003). On the other hand, the application of $PGPR_2$ did not show a significant effect on the amount of soil AK in any of the irrigation water salinity levels. However, inoculation with $PGPR_1$ at salinity levels of 5 and 10 dS.m^{-1} significantly increased the value of this parameter by 10 and 18%, respectively, compared to the control at same salinity levels. The highest amount of rhizosphere soil AK (216 mg.kg^{-1}) was obtained from the application of $PGPR_1$ at the irrigation water salinity level of 10 dS.m^{-1} (Table 3). Tang et al (2023) indicated the inoculation with PGPR significantly increased the concentration of soil available N, P, and K as well as soil urease, sucrase, dehydrogenase, and protease activities in the alfalfa rhizosphere.

Table 3. The mutual effect of PGPR and irrigation water salinity on the available P, available K, EC_e and Ca/Mg in the rhizosphere soil

PGPR	Water salinity (dS.m^{-1})			Water salinity (dS.m^{-1})		
	0	5	10	0	5	10
	AP (mg.kg^{-1})			AK (mg.kg^{-1})		
$PGPR_0$	5.76 c	5.40 c	4.28 d	156 ef	158 def	182 b
$PGPR_1$	7.84 b	7.75 b	7.14 b	165 cde	175 bc	216 a
$PGPR_2$	10.3 a	8.05 b	7.63 b	146 f	172 bcd	181 b
	EC_e (dS.m^{-1})			Ca/Mg		
$PGPR_0$	1.67 e	3.11 c	6.31 a	1.18 e	2.93 c	4.25 a
$PGPR_1$	1.83 e	2.68 cd	5.65 b	1.19 e	3.56 b	4.33 a
$PGPR_2$	2.24 de	2.95 c	5.50 b	2.09 d	3.15 bc	4.40 a

For each parameter, values followed by the same letter are not significantly different ($p \leq 0.05$) according to LSD test.

3.4. Concentration of soluble Na, Ca, Mg, HCO_3, Ca/Mg and sodium absorption ratio (SAR)

The analysis of variance illustrated that the content of soluble Na, Ca, Mg, and Ca/Mg and SAR were significantly affected by PGPR inoculation, irrigation water salinity levels and mutual effects of PGPR and irrigation water salinity ($p \leq 0.05$). Also, the concentration of HCO_3 in the rhizosphere soil solution was affected ($p \leq 0.01$) only by main effect of irrigation water salinity (Table 2).

Based on the results, an increase in the irrigation water salinity levels caused an increase in the content of rhizosphere soil Na_s (Table 4). With application of 5 and 10 dS.m^{-1} water salinity levels, the content of Na_s in the rhizosphere soil of pistachio seedlings drastically increased by 3.5 times and 5.2 times compared to the control, respectively. In general, the concentration of Na in the soil solution and soil's absorption complex of saline soils is high, which is the result of disturbance and imbalance in the absorption of water and nutrients by the plant and damage to the physical, chemical and biological properties of the soil (Ahmet, 2011). In the present study, although the ratio of Na/Ca was not affected by irrigation water salinity, the ratio of Na/Mg increased with the increase of irrigation water salinity levels. High concentration of Na in the soil leads to high ratios of Na/Mg, Na/Ca and Na/K, which causes an imbalance of nutrients in the soil and plants (Van Tan and Thanh, 2021). Therefore, it is necessary to reduce the concentration of this ion in soil and soil's absorption complex. Nevertheless, the application of rhizobacteria had no significant effect on the amount of Na_s in the rhizosphere soil at water salinity levels of 0 and 5 $dS.m^{-1}$. But inoculation with $PGPR_1$ and $PGPR_2$ isolates at irrigation water salinity level of 10 $dS.m^{-1}$ significantly reduced the concentration of Na_s in rhizosphere by 12 and 14%, respectively, in comparison with the control at this water salinity level (Table 4). Also, the results showed that as salinity levels raised, Ca_s significantly increased. Water salinity stress at 5 and 10 $dS.m^{-1}$ levels caused a significant increase of 4.3 times and 8.8 times, respectively, in the rhizosphere soil Ca_s content compared to the control. In saline soils, the concentration of Ca usually increases with the increase in the amount of salts. Increasing the amounts of Ca and Mg in saline soils and especially sodic soils is important because of the effect of these elements on the reduction of SAR (Hussain et al., 2016). The use of PGPRs only at water salinity level of 10 $dS.m^{-1}$ was effective on the content of Ca_s in rhizosphere. Treatment with $PGPR_1$ and $PGPR_2$ isolates significantly decreased rhizosphere soil Ca_s concentration by 14 and 13%, respectively, compared to the control at same salinity levels (Table 4). The results showed that irrigation water salinity levels of 5 and 10 $dS.m^{-1}$ increased the amount of soluble Mg in the rhizosphere soil by 1.7 and 2.5 times, respectively, compared to the control treatment. On the other hand, inoculation with rhizobacteria decreased this parameter in the rhizosphere soil. For example, the use of $PGPR_1$ and $PGPR_2$ at salinity levels of 10 $dS.m^{-1}$ significantly reduced the content of Mg_s by 14 and 16%, respectively, in comparison with the same salinity levels (Table 4). Orhan et al. (2006) reported that the use of PGPR strains caused a significant increase in N, P, K, Ca, Mg, Fe, Mn and Zn elements content in the soil. They stated that the increase in the availability of minerals in the soil due to bacterial applications can be attributed to the decrease in the pH of the soil rhizosphere and the increase in the mineralization of the organic complex. Based on the obtained results, the salinity level of 5 $dS.m^{-1}$ had no significant effect on the concentration of HCO_3. Although the application of salinity level of 10 $dS.m^{-1}$ increased the amount of this anion in the rhizosphere soil solution by 23% compared to the control treatment (Fig. 3). According to the results of present study, with the increase of irrigation water salinity to 5 and 10 $dS.m^{-1}$, the ratio of Ca/Mg in the rhizosphere soil solution significantly increased from 1.18 to 2.93 and 4.25 $mg.L^{-1}$, respectively. Also, inoculation with PGPR2 isolate significantly increased Ca/Mg in the rhizosphere soil solution by 50% relative to the non-inoculated control in non-saline conditions. The ratio of this parameter at the irrigation water salinity level of 5 $dS.m^{-1}$ with the application of $PGPR_1$ also showed an increase of 21% compared to this level of salinity without the use of PGPRs (Table 3). The results of the present study showed that by increasing the salinity of irrigation water to 5 and 10 $dS.m^{-1}$, the amount of SAR in the rhizosphere soil solution increased by 2.1 and 2.3 times, respectively, compared to the control (Table 4). The use of saline water in saline and saline-sodic soils increases the rate of sodium absorption (SAR) due to the increase in leaching of Na from the surface layers of the soil (Akhtar et al., 2003). Other studies have also shown that increasing the salinity of irrigation water increases the sodium absorption ratio in the soil (Mostafazadeh-farad et al., 2007). However, although the use of PGPRs at salinity level of 10 $dS.m^{-1}$ did not have a significant effect on the amount of SAR, but the inoculation with $PGPR_1$ and $PGPR_2$ isolates significantly reduced the value of this index in rhizosphere soil solution at salinity level of 5 $dS.m^{-1}$ by 13 and 14%, respectively, compared to the same salinity level (Table 4). Damodaran et al. (2014) indicated that the inoculation with bacteria reduced the soil SAR, soil pH and total carbonates in the rhizosphere soils, enhancing nutrient mobilization as well as favorable plant growth.

Table 4. The mutual effects of PGPR and irrigation water salinity on the soluble Na, Ca, and Mg and SAR in the rhizosphere soil

PGPR	Water salinity ($dS.m^{-1}$)			Water salinity ($dS.m^{-1}$)		
	0	5	10	0	5	10
	Na_s ($mg.L^{-1}$)			Ca_s ($mg.L^{-1}$)		
$PGPR_0$	138 d	479 c	721 a	62 d	269 c	551 a
$PGPR_1$	188 d	414 c	632 b	85.7 d	295 c	473 b
$PGPR_2$	205 d	413 c	614 b	116 d	275 c	477 b
	Mg_s ($mg.L^{-1}$)			SAR ($mEq.L^{-1}$)$^{0.5}$		
$PGPR_0$	52 f	91.3 c	129 a	3.12 e	6.40 b	7.20 a
$PGPR_1$	71.7 de	82.3 cd	110 b	3.61 de	5.48 c	6.78 ab
$PGPR_2$	55.7 ef	87.0 cd	108 b	3.91 d	5.54 c	6.58 ab

For each parameter, values followed by the same letter are not significantly different ($p \leq 0.05$) according to LSD test.

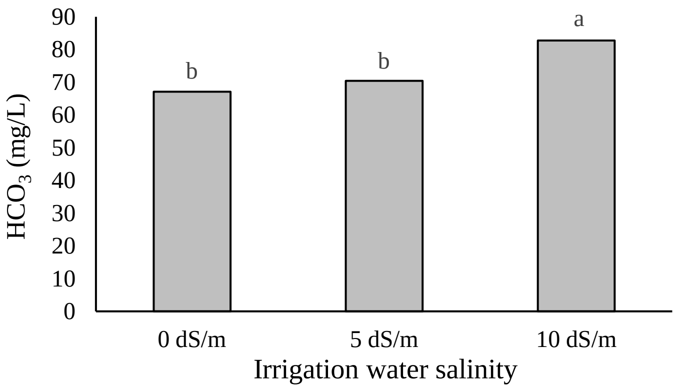

Fig. 3. Main effect of irrigation water salinity on the rhizosphere soil bicarbonate (HCO_3) content. Within each graph, values followed by the same letter are not significantly different ($p \leq 0.05$) according to LSD test.

3.5. Mass soil moisture content (Θ_m)

According to the results of analysis of variance (Table 2), the main and interaction effect of PGPRs and irrigation water salinity on the soil moisture content (Θ_m) were significant ($p \leq 0.05$).

The results showed that with the increase in water salinity, the amount of soil moisture increased.

The use of salinity levels of 10 $dS.m^{-1}$ caused a 58% increase in soil moisture content compared to the control (Fig. 4). Despite the relatively high amount of water in saline soils, the ability of plants to absorb water decreases due to increased osmotic pressure and limited root growth. High-salinity water irrigation significantly increased the water content of the soil by influencing the plant's absorption of water.

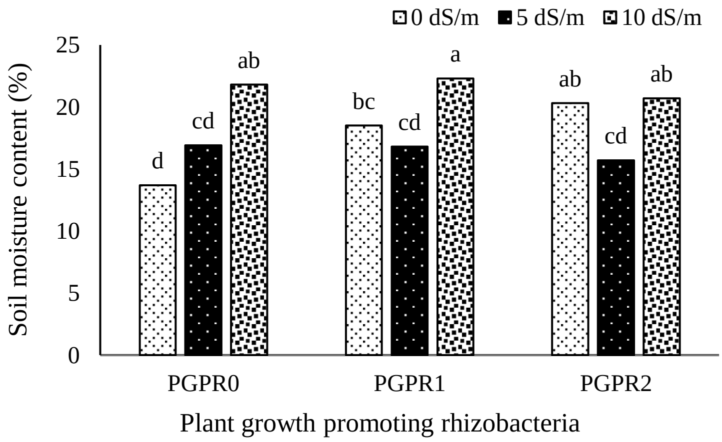

Fig. 4. The effect of PGPR × irrigation water salinity on the rhizosphere soil moisture content (Θ_m). Within each graph, values followed by the same letter are not significantly different ($p \leq 0.05$) according to LSD test.

Also, Zhang et al. (2019a) reported that there was a positive correlation between soil moisture and salinity. On the other hand, inoculation with rhizobacteria increased the amount of soil moisture under non-saline conditions. Treatment with $PGPR_1$ and $PGPR_2$ isolates significantly increased the soil moisture content by 36 and 48% at 0 $dS.m^{-1}$ salinity level, respectively, in comparison with the non-inoculated control. However, the application of rhizobacteria did not have a significant effect on the amount of soil moisture in saline conditions.

The highest (22.3%) amount of soil moisture was obtained from the application of $PGPR_2$ isolate at the salinity level of 10 $dS.m^{-1}$ (Fig. 4). Microorganisms can help maintain soil moisture by producing different organic compounds. Synthesize of exo-polysaccharide by soil rhizobacteria plays a critical role in improving the soil structure and thus enhances soil permeability. This compound can have a positive effect on retaining more water in the soil and ultimately maintain plant growth under water stress (Alaskar and Al-Shwaiman, 2023).

4. Conclusion

In recent years, the decrease in precipitation along with the increase in air temperature has caused an increase in evaporation and transpiration from the soil and ultimately a decrease in soil moisture, especially in agricultural lands in arid/semi-arid areas. These factors have caused an increase in the extraction of water from underground sources for agriculture, which, in addition to land subsidence and other environmental effects, has reduced the quantity and quality of underground water. Therefore, the use of water sources with different degrees of salinity for agricultural production is expanding. Irrigation of lands with saline water, in addition to reducing the yield of plants, has also had negative effects on the physical, chemical and biological properties of the soil. Therefore, it is necessary to use new methods to reduce the accumulation of salts and improve the properties of soils irrigated with saline water sources. In this research, the effect of PGPRs on various characteristics of irrigated soil with different salinity levels was evaluated. The results showed that although the use of saline water increased content of EC, SAR, and Na_s, and decreased the rate pH, AP and OM in the rhizosphere soil, but inoculation with PGPR isolates improved various soil properties, including AP, AK, OM, Θ_m, SAR and pH at different salinity levels. By producing various compounds such as organic acids and protons, PGPRs reduce the pH of the rhizosphere environment and, as a result, increase the availability of elements such as P in the soil. Also, increasing the population and activity of bacteria in the rhizosphere environment can help to increase root secretions and organic compounds in the soil. The bacteria used in this research had the ability to dissolve tri-calcium phosphate and produce auxin and siderophore in laboratory conditions. Therefore, the use of microorganisms with the ability to produce growth-stimulating and soil-modifying compounds can improve various characteristics of saline soils and plant growth.

5. Disclosure Statement

No potential conflict of interest was reported by the authors.

6. References

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