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Water Use and Yield Responses of Chile Pepper Cultivars Irrigated with Brackish Groundwater and Reverse Osmosis Concentrate

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Abstract: Freshwater availability is declining in most of semi-arid and arid regions across the world, including the southwestern United States. The use of marginal quality groundwater has been increasing for sustaining agriculture in these arid regions. Reverse Osmosis (RO) can treat brackish groundwater, but the possibility of using an RO concentrate for irrigation needs further exploration. This greenhouse study evaluates the water use and yield responses of five selected chile pepper (*Capsicum annuum* L.) cultivars irrigated with natural brackish groundwater and RO concentrate. The four saline water treatments used for irrigation were tap water with an electrical conductivity (EC) of 0.6 dS m^{-1} (control), groundwater with EC 3 and 5 dS m^{-1}, and an RO concentrate with EC 8 dS m^{-1}. The evapotranspiration (ET) of all chile pepper cultivars decreased and the leaching fraction (LF) increased, particularly in the 5 dS m^{-1} and 8 dS m^{-1} irrigation treatments. Based on the water use efficiency (WUE) of the selected chile pepper cultivars, brackish water with an EC $\leq$ 3 dS/m could be used for irrigation in scarce freshwater areas while maintaining the appropriate LFs. A piecewise linear function resulted in a threshold soil electrical conductivity (EC_e) ranging between 1.0–1.3 dS m^{-1} for the tested chile pepper cultivars. Both piecewise linear and sigmoid non-linear functions suggested that the yield reductions in chile peppers irrigated with Ca^{2+} rich brackish groundwater were less than those reported in studies using an NaCl-dominant saline solution. Further research is needed to understand the role of supplementary calcium in improving the salt tolerance of chile peppers.

Keywords: *Capsicum annuum*; salinity; evapotranspiration; leaching fraction; calcium

1. Introduction

Freshwater is an integral resource for all ecological and social activities, including food and energy production, industrial growth, and human health. As freshwater resources are unevenly and irregularly distributed [1], many arid and semi-arid parts of the world are facing acute water shortages. Similar water shortages affect the southwestern United States due to low rainfall and high evapotranspiration [2]. As agriculture is the largest consumer of freshwater [3], the use of marginal quality water resources, including brackish groundwater, has been increasing [4,5]. About 75% of the groundwater aquifers in the southwestern United States have brackish water, with an electrical conductivity (EC) of > 3 dS/m [6,7]. Additionally, the desalination of brackish groundwater through Reverse Osmosis (RO) produces potable, low saline water and high saline–sodic wastewater known as RO concentrate [7]. The application of desalinated water for irrigation can promote soil hydrological functions [8]. However, the disposal of RO concentrate from an inland desalination system can be problematic, and its sustainable management is a major environmental challenge that restricts the widespread application of RO for groundwater desalination. RO concentrate could serve as a potential source of irrigation for the production of salt-tolerant crops, along with brackish water available from natural saline aquifers [9,10], which will consequently encourage desalination through RO in freshwater scarce-areas.

Continued irrigation with brackish groundwater can lead to salt accumulation in soil which can lower yields, although plants differ extensively in their response to soil salinity. Most crop plants are glycophytes, which can be affected by even a moderate level of soil salinity [11]. Instead of accumulating salts, most glycophytes produce some chemicals (sugars and organic acids) to raise the concentration of constituents in the root cell. This process requires more energy, and thus their crop growth and yield are more susceptible to damage compared to halophytes [12]. Moreover, salt tolerance within the glycophytes group varies widely [13]. Sugarbeet (*Beta vulgaris* L.) and wheat (*Triticum aestivum* L.) are considered salt-tolerant; potato (*Solanum tuberosum* L.), sunflower (*Helianthus annuus* L.), maize (*Zea mays* L.), soybean (*Glycine max* L. Merrill.), and tomato (*Solanum lycopersicum* L.) are moderately salt-sensitive; and chickpea (*Cicer arietinum* L.) and lentil (*Lens culinaris* Medic.) are salt-sensitive [14].

Chile pepper (*Capsicum annuum* L.), also a glycophyte, is an important cash crop of the southwestern United States, cultivated over an area of 20,000 acres annually [15]. It is classified as moderately salt-sensitive, with a saturated soil paste extract EC (EC_e) threshold value of 1.5 dS m^{-1} [16]. Studies have also reported threshold values between an EC_e of 0–2 dS/m for peppers [17,18]. To the best of our knowledge, most studies on peppers have used NaCl as the sole or the dominant salinizing agent [17–21]. However, Na^+, Ca^{2+}, and Mg^{2+} are the dominant cations, and Cl^-, $SO_4{}^{2-}$, and $HCO_3{}^-$ are the dominant anions in most groundwater across the world [22]. It has been suggested that the adoption of salinizing solutions with a single salt may result in ambiguous and erroneous interpretations about plant responses to salinity [23]. Only a few accounts are available involving the use of natural brackish groundwater for growing chile peppers [24]. Therefore, more research on the use of natural brackish groundwater and RO concentrate for irrigating chile pepper cultivars is needed.

The use of brackish groundwater often brings risks and obligations to an agricultural system. The application of insufficient water quantities causes a lowering of the osmotic potential of soil water, ultimately causing stress to the plants [25], whereas over-application is economically ineffectual and could exacerbate salinity problems, including groundwater contamination [26]. There is very limited information available on the evapotranspiration (ET) responses of the chile pepper to varying irrigation salinity. An understanding of water uptake by the chile pepper under contrasting saline water treatments would allow the exploration of irrigation scheduling protocols for regions utilizing brackish groundwater. Therefore, the objectives of this study were to (1) quantify the influences of brackish groundwater and RO concentrate irrigation on the leaching fraction and water use of five chile pepper cultivars; and (2) determine their yield responses to the resulting soil salinity.

2. Materials and Methods

2.1. Experimental Set Up

The study was conducted in a greenhouse located at the Fabian Garcia Science Center of New Mexico State University (NMSU), Las Cruces, New Mexico (32.2805° N latitude and 106.770° W longitude at an elevation of 1186 m above sea level), consistent with the potential of greenhouse chile pepper production in New Mexico [27] and the New Mexico Department of Agriculture regulation of no land application of water with an EC > 4 dS m^{-1}. The chile pepper cultivars selected for this study were AZ1904 (Curry Chile and Seed, Pearce, AZ, USA), Paprika LB25 (Biad Chile, Leasburg, NM, USA), Paprika 3441 (Olam, Las Cruces, NM, USA), and two NMSU varieties: NuMex Joe E. Parker and NuMex Sandia Select. The natural brackish groundwater and RO concentrate provided by the Brackish Groundwater National Desalination Research Facility (BGRNDRF), Alamogordo, were used in the irrigation treatments (Table 1). Sandy loam soil (78.7% sand, 11% silt, and 10.3% clay) with an initial EC_e of 0.87 dS/m was air-dried, crushed, and sieved through a 4 mm sieve. A soil mix was prepared by mixing soil, sand, and organic peat in the ratio 8:1:1 on a volume basis. The soil mix was sterilized in an oven at 80 °C for at least 30 min. The cylindrical pots used in the experiment were 0.14 m in diameter and 0.25 m in depth. The bottom of each pot was perforated and covered with cheesecloth and then gravels to allow free drainage. The soil packing was done in 5 cm depth increments to obtain a bulk density of 1.36 g/cm^3. The average day and night temperatures recorded during the study period (148 days) were 31.8 ± 0.2 °C and 24.4 ± 0.1°C.

Table 1. Mean (standard error) for chemical properties of the four saline water treatments over the growing period.

	EC dS m^{-1}	Ion Concentration (meq/L)					
		Mg	Ca	Na	K	Cl	SO_4
Tap water	0.6	0.75 (0.01)	2.28 (0.01)	2.73 (0.37)	0.15 (0.01)	1.64 (0.07)	1.58 (0.02)
Well 1	3	8.65 (0.01)	11.90 (0.38)	8.94 (0.18)	0.16 (0.00)	11.91 (0.05)	18.70 (0.79)
Well 2	5	15.24 (0.28)	17.60 (2.08)	19.04 (1.92)	0.21 (0.02)	16.86 (1.72)	38.78 (3.56)
RO conc.	8	25.81 (0.16)	29.43 (2.69)	33.51 (2.96)	0.37 (0.06)	31.23 (5.04)	67.15 (7.43)

Tap water is the control; EC: electrical conductivity; RO conc.: reverse osmosis concentrate.

2.2. Saline Irrigation Treatments

The four irrigation water treatments selected were tap water with the EC 0.6 dS m^{-1}, brackish groundwater with the EC 3 and 5 dS m^{-1}, and an RO concentrate with the EC 8 dS m^{-1}. Before planting, the soil was washed three times with tap water to remove any pre-existing salts, and then the soil salinity was raised to the saline treatment level by irrigating twice with each of the saline water treatments. Four seeds of each chile pepper were sown in pots at a soil depth of 1–2 cm. After emergence, the seedlings were thinned, and only one vigorous seedling was retained in each pot. The irrigation water treatments were continuously applied at an interval of 3–4 days during the experiment period, based on the change in weights of some reference pots. The plants were fertigated using a water-soluble synthetic fertilizer (Miracle-Gro®; 15-30-15) at 2 g L^{-1} every six weeks.

2.3. Data Collection

The same amount of irrigation (I) was applied manually to each pot, and the deep percolation (D) was measured by collecting all the water coming out of the bottom of each pot. The ET was calculated using the following water balance equation:

$$ET = P + I - D - R - \Delta S \quad (1)$$

where ET is the actual crop evapotranspiration (cm), P is the precipitation (cm), I is the irrigation amount (cm), D is the deep percolation (cm), R is the runoff (cm), and ΔS is the change in soil water storage (cm). As the experiments were carried out in a greenhouse, the precipitation and runoff were zero. The change in soil water storage (ΔS) was determined from the difference in weights of the pots at planting and final harvest. The leaching fraction (LF) was calculated for every irrigation as the ratio of D and I. The pods were hand-harvested at the horticultural green mature stage, and the fresh pod weights were measured. The water use efficiency (WUE) was calculated as the ratio of the total yield to total crop ET.

At the end of the experiments, the top 10 cm layer of soil was collected from each pot and saturated soil paste extracts were prepared using composite samples and analyzed for their EC_e, magnesium (Mg), calcium (Ca), and sodium (Na) ion concentrations [28]. The sodium adsorption ratio (SAR) was determined using the following equation:

$$SAR = \frac{[Na^+]}{\sqrt{\frac{([Ca^{2+}]\,[Mg^{2+}])}{2}}} \quad (2)$$

2.4. Salinity-Yield Response Equations

The relative yield (Y_r) was obtained as the ratio of actual total yield and maximum total yield for each cultivar. The relationship between the EC_e at the end of the growing season and the relative yield was predicted using the piecewise linear function [16]:

$$Y_r = 1 - b\,(EC_e - a) \quad (3)$$

where a = the salinity threshold (dS m^{-1}); b = the yield reduction, or slope (per dS m^{-1}); and EC_e = the EC of saturated soil extracts from the root zone (dS m^{-1}).

Similarly, the relationships between the Y_r and EC_e of each cultivar were best-fitted with the sigmoid non-linear function [29]:

$$Y_r = \frac{1}{\left(1 + \frac{c}{c_{50}}\right)^p} \quad (4)$$

where Y_r = relative yield; c = the EC of saturated soil extracts from the root zone (dS m^{-1}), c_{50} = root zone EC_e at which the yield had declined by 50% (dS m^{-1}) and p is the exponential constant.

2.5. Statistical Analysis

The cylindrical pots for the experiments were arranged in a completely randomized factorial design with eight replicates of each cultivar and a saline water treatment combination. A two-way analysis of variance (ANOVA) was used to identify the significant differences at alpha 5% applying general linear model procedure (PROC GLM) for ET, D, ΔS, and WUE [30]. The means were separated using the least significance difference (LSD) post hoc test at a 5% significance level ($p \leq 0.05$). The relationships of the EC_e with the concentrations of Mg, Ca, and Na ions and SAR were tested for linear, quadratic and exponential functions using Sigmaplot version 14 (Systat Software Inc., San Jose, CA, USA), and the best fit was selected based on regression statistics. The relative yield response to the EC_e was best fitted to the piecewise linear and sigmoid non-linear functions using the 'nls2' package in R [31].

3. Results and Discussion

3.1. Leaching Fraction over Growing Season

The leaching fractions (LF) for AZ 1904, NuMex Joe E. Parker, NuMex Sandia Select, Paprika LB25, and Paprika 3441 over the growing season are shown in Figure 1a–e, respectively. For almost one month after planting, LFs were similar for cultivars grown using the four saline water treatments. Over time, variations in the LF appeared and became a function of the irrigation water salinity for all five cultivars. Among the four irrigation water treatments, the LFs for the 0.6 dS m^{-1} (control) treatment were the least, while they were the most for the 8 dS m^{-1} RO irrigation treatment throughout the growing season. The differences in LFs of between 0.6 dS m^{-1} and 3 dS m^{-1} were considerably smaller compared to the other two treatments in all five cultivars.

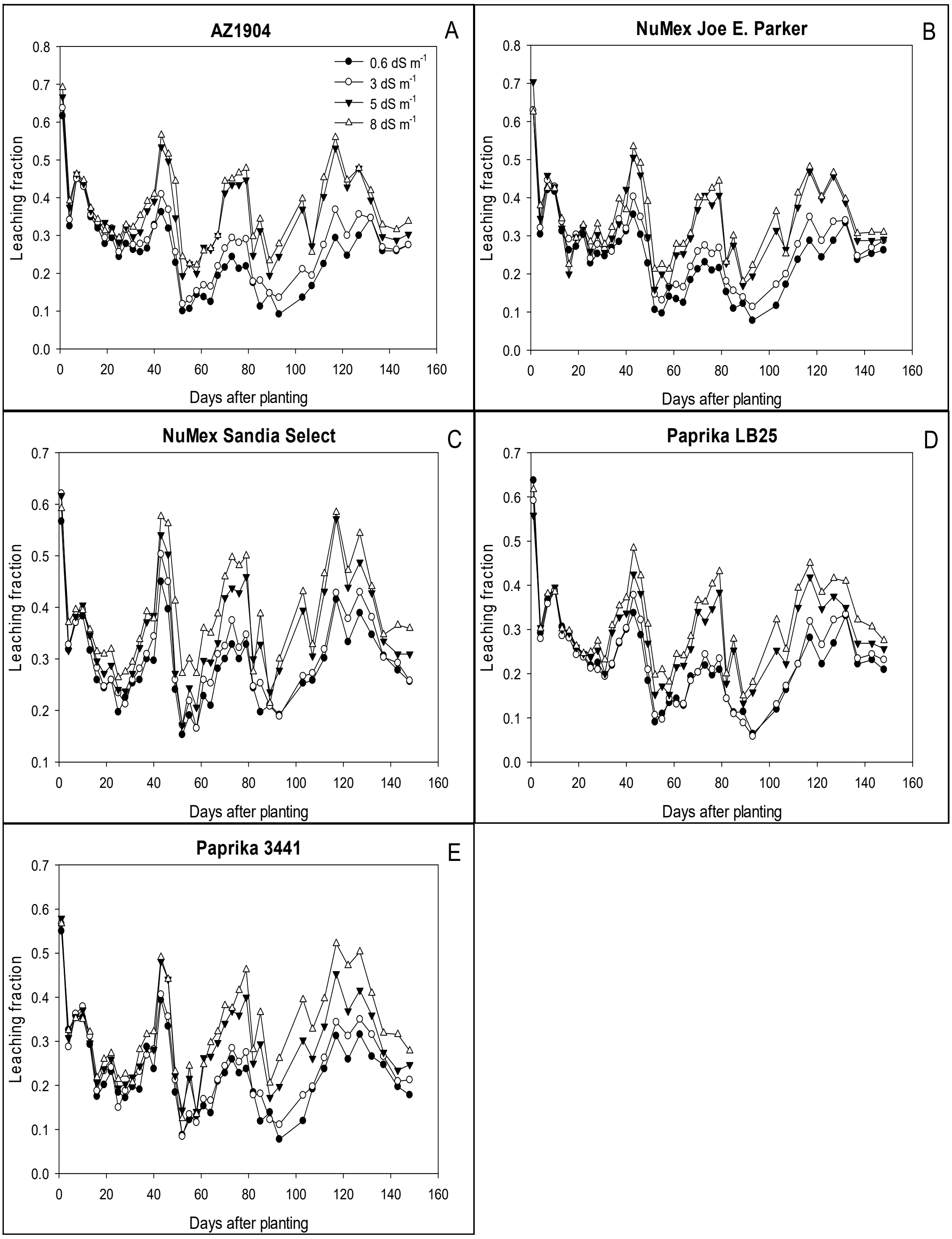

Figure 1. Effect of different saline water treatments on the leaching fractions of (**A**) AZ1904, (**B**) NuMex Joe E. Parker, (**C**) NuMex Sandia Select, (**D**) Paprika LB25, and (**E**) Paprika 3441 over the growing season.

The observed higher LFs under the saline treatments could be due to the self-adjusting nature of the plants under water and osmotic stresses. In response to saline irrigation water, the transpiration rate of chile pepper plants would have decreased due to the reduction in water potential caused by accumulated salts at the root zone [32]. Similar increases in LFs at a given irrigation rate occurred due to the reduction in transpiration rates for the bell pepper (*Capsicum annuum* L.) [33]. In the areas with a shallow water table, more deep percolation could cause secondary salinization [34]. Therefore, it is advisable to explore irrigation scheduling protocols before the application of the concentrate in a field to maintain the soil and groundwater quality [7].

3.2. Water Balance

A total irrigation of 106.3 cm was applied to each pot during the experiment period. The influence of irrigation water salinity on the total crop ET, ΔS and D are shown in Table 2. There was no significant interaction ($p > 0.05$) between the saline treatments and cultivars for D, ΔS, and ET, while the significant main effects of both the saline treatments and cultivars were observed. The total ET of five chiles showed a significant decrease ($p \leq 0.05$) with increasing irrigation water salinity. The highest cumulative ET of the five cultivars was noted at 0.6 dS m^{-1} (control), which was only 4% greater than 3 dS m^{-1}; however, it was around 12% and 17% greater compared to the 5 dS m^{-1} and 8 dS m^{-1} treatments, respectively. The total deep percolation was inversely related to the total crop ET and significantly increased from 24% of the total irrigation amount in the 0.6 dS m^{-1} (control) to 35% in the 8 dS m^{-1} (RO concentrate).

Table 2. Effect of irrigation water salinity on the total deep percolation, change in soil water storage, and evapotranspiration of five chile pepper cultivars.

Treatment	Deep Percolation (cm)	Change in Storage (cm)	Evapotranspiration (cm)
Salinity (S; dS m^{-1})			
0.6	25.06 d	1.56 a	76.99 a
3	28.06 c	1.48 ab	74.07 b
5	33.26 b	1.42 bc	68.93 c
8	36.73 a	1.34 c	65.55 d
LSD (0.05)	1.36	0.09	1.37
Cutivars (C)			
AZ 1904	32.55 b	1.42 a	69.65 c
NuMex Joe E. Parker	30.80 c	1.45 a	71.37 b
NuMex Sandia Select	34.77 a	1.50 a	67.34 d
LB 25	27.56 d	1.45 a	74.60 a
3441	28.22 d	1.43 a	73.97 a
LSD (0.05)	1.52	0.11	1.53
C X S	NS	NS	NS

† Values within each column followed by same letter(s) are not significantly different according to the least significance difference test ($p \leq 0.05$). NS = non-significant at $p \leq 0.05$. Irrigation amount applied was 103.6 cm for all of the treatments.

The reduction in ET with increasing water salinity could be attributed to retarded plant growth and a decrease in bioavailable water under saline soil conditions. The water uptake of plants, through apoplastic and symplastic pathways at roots, is largely regulated by the osmotic and matric potentials of the root zone [35]. Under saline soil conditions, the reduced osmotic potential affects the free energy of water and decreases the root water uptake by plants, which leads to a reduction in the plant growth and ET and thus an increase in leaching [36]. In addition, a salt crust formed at the top soil layer due to saline irrigation could reduce evaporation from the soil surface [37]. Therefore, the surface crusting (visual observations) could also have played some role in reducing the total ET of the chile pepper.

In contrast to the total ET, NuMex Sandia Select had the greatest D, while Paprika LB 25 and 3441 had the minimum among the five cultivars. The differences noticed in the cumulative ET among the cultivars could be attributed to natural variations in the growth of the cultivars. The overall change in soil water storage was small in all of the pots, but it decreased significantly across irrigation treatments from 1.56 cm in the 0.6 dS m^{-1} to 1.34 cm in the 8 dS m^{-1} irrigation water treatment.

3.3. Water Use Efficiency

No significant interaction between the saline treatments and cultivars ($p > 0.05$) was observed for the WUE, while significant reductions ($p \leq 0.05$) in the WUE were noted with the increasing salinity of the irrigation water (Figure 2A). The reduction in the WUE was only 9% in the 3 dS m^{-1} compared to the control treatment, while it was 38% and 42% in the 5 and 8 dS m^{-1} water treatments, respectively. The WUE is generally treated as an important physiological indicator of crops that are grown in water-scarce conditions. As the WUE of chile peppers irrigated with 3 dS/m was not much different from those irrigated with 0.6 dS/m, a slightly brackish groundwater (<3 dS m^{-1}) might be considered for irrigating chile peppers if brackish groundwater is the only available source of irrigation, while simultaneously monitoring salts in the leachate water and soil. However, significant reductions can occur with a further increase in the salinity of the irrigation waters. A similar reduction in the WUE with an increased irrigation water salinity was reported in tomato [38,39]. The average WUE of the five chile pepper cultivars in this study was similar and was in agreement with results reported by Reina-Sanchez et al. (2005) for four tomato cultivars irrigated with saline water (Figure 2B) [40].

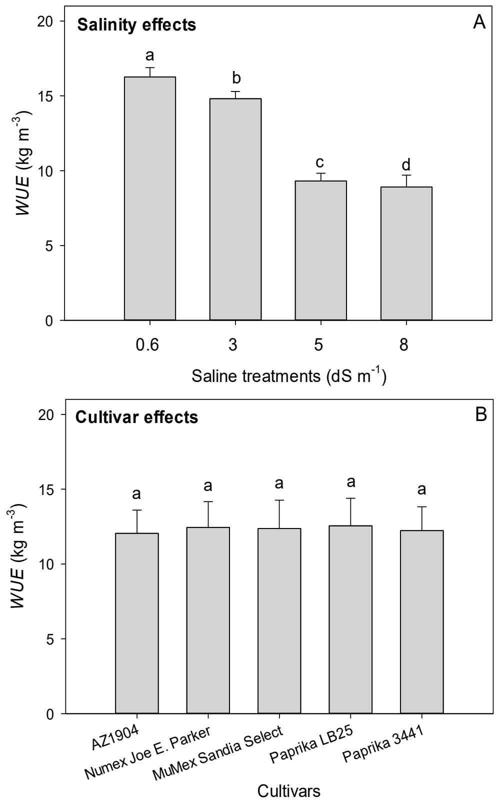

Figure 2. (**A**) Water use efficiency (WUE) of the chile pepper cultivars under four saline irrigation waters, and (**B**) the WUE of five chile pepper cultivars across saline irrigation waters. Bars with the same letters are not significantly different according to the least significance difference test at $p \leq 0.05$.

3.4. Accumulation of Mg^{2+}, Ca^{2+} and Na^+ Cations in Soil

There were no significant differences among the cultivars ($p > 0.05$) for the magnesium, calcium and sodium concentrations and the sodium adsorption ratios of saturated soil paste extracts (data not presented). Although all three Mg^{2+}, Ca^{2+}, and Na^+ cation concentrations increased significantly ($p \leq 0.05$) with the EC_e, different responses were noted, especially at EC_e higher than 9 dS m^{-1} (Figure 3A). A linear relationship of Mg^{2+} concentration was obtained with the EC_e, while the response of Na^+ and Ca^{2+} was positive exponential and negative exponential, respectively. It was observed that the Na/Ca ratio of the soil paste extract increased from 1.13 in the 0.6 dS m^{-1} to 1.87 in the 8 dS m^{-1}

treatment. The reason could be the displacement of Ca^{2+} by Na^+ and the subsequent Ca^{2+} leaching under high Na^+ concentrations in soil [41]. The SAR increased linearly ($p \leq 0.05$) with the increasing EC_e (Figure 3B), which could be well explained by a greater increase in Na^+ than in Ca^{2+} concentration under high salinity.

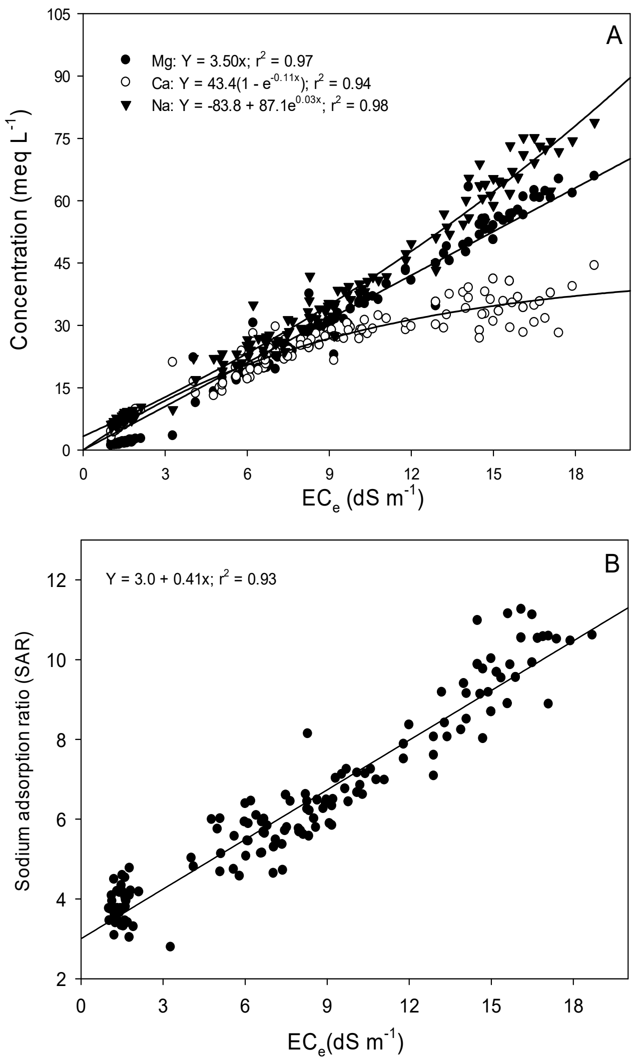

Figure 3. Relationships of (**A**) magnesium (Mg), calcium (Ca), and sodium (Na) ions buildup and (**B**) the sodium adsorption ratio (SAR) with the salinity level (EC_e) of soil irrigated with brackish water and reverse osmosis concentrate.

3.5. Yield Responses to Root-Zone Salinity

The relative yield responses of five chile pepper cultivars to the EC_e were similar and considerably well explained by both piecewise linear and sigmoid non-linear functions; though the sigmoid function resulted in a slightly better fit for each of the five cultivars, as evident by their higher coefficient of determination (r^2; 0.87–0.91) and lower residual sum of squares (RSS) values (Table 3). Likewise, the overall yield responses of chile pepper cultivars were slightly better explained by the sigmoid function compared to the piecewise function. The threshold value (a) estimated using the piecewise linear function ranged between 1.04–1.33 dS m^{-1}, with Numex Joe E. Parker and Paprika LB25 having the lowest and greatest a value, respectively, among the cultivars. Whereas, both Paprika 3441 and NuMex Sandia Select resulted in threshold values (1.09 & 1.12 dS m^{-1}) close to the observed value of 1.10 dS m^{-1} for all the cultivars. The a values obtained in this study were lower than the earlier threshold values of 1.5–1.8 dS m^{-1} suggested for the peppers [16,17,42]. Additionally, the determined slope (b) values of 0.038–0.046 were also lower as compared to the earlier reported values of 0.14 [43] and 0.12 [42].

Table 3. Regression statistics for two response functions applied to yield responses of five chile pepper cultivars against soil salinity.

	Piecewise Linear Function				
	***a* (dS m^{-1})**	***b* (dS m^{-1})$^{-1}$**	r^2	*RSS*	*N*
AZ1904	1.19	0.044	0.88	0.21	32
NuMex Joe E. Parker	1.04	0.045	0.90	0.24	32
Numex Sandia Select	1.12	0.045	0.89	0.25	32
Paprika LB25	1.33	0.046	0.85	0.25	32
Paprika 3441	1.09	0.038	0.89	0.17	32
All cultivars	1.10	0.043	0.87	1.18	160
	Sigmoid non-linear function				
	c_{50} (dS m^{-1})	p	r^2	*RSS*	*N*
AZ1904	12.22	2.110	0.89	0.18	32
NuMex Joe E. Parker	11.61	1.633	0.91	0.19	32
Numex Sandia Select	10.75	1.262	0.89	0.32	32
Paprika LB25	12.01	1.761	0.87	0.16	32
Paprika 3441	13.55	1.537	0.90	0.12	32
All cultivars	12.11	1.618	0.88	0.94	160

a: salinity (EC_e) threshold; b: slope; c_{50}: EC_e at which yield is reduced by 50%; p: regression constant for sigmoid function.

The 50% yield reduction (c_{50}) estimations from sigmoid non-linear functions were ranged between 10.75–13.55 dS m^{-1}, which was in agreement with the range (12.15–14.21 dS m^{-1}) predicted using piecewise linear equations for the chile pepper cultivars. The lowest c_{50} (10.75 dS m^{-1}) was noted for NuMex Sandia Select, while Paprika 3441 had the greatest c_{50} of 13.55 dS m^{-1}. The other three varieties showed similar yield reductions with an increase in soil salinity, and their c_{50} values were ranged between 12.01–12.22 dS m^{-1}. The observed c_{50} values of all the chile peppers were much higher than the 6 dS m^{-1} proposed for the peppers [42,44]. Furthermore, the constant p values ranging between 1.26–2.11 were comparatively lower than the value of 3.0 suggested for most of the crops, including peppers [45].

Lower yield reductions in chile peppers against the soil salinity compared to previous reports could be attributed to the calcium dominated brackish groundwater used in this study. The considerable amount of calcium in the natural saline irrigation treatments has been reported to ameliorate the salinity's impact on plants [46]. Calcium plays regulatory roles in the metabolism, water transport, and root hydraulic conductivity of plants under salt stress [47,48]. Moreover, high calcium levels can shield the cell membrane from detrimental salinity effects [49].

4. Conclusions

This study evaluated the effects of natural brackish groundwater and RO concentrate irrigation on the water use, leaching fraction, and yield responses of chile pepper cultivars. Saline irrigation caused a reduction in the water uptake of the chile peppers and increased LFs, particularly in the 5 dS m^{-1} and the 8 dS m^{-1}. The WUE was not substantially different between 0.6 and 3 dS m^{-1} but decreased significantly in the other two higher salinity treatments. Therefore, irrigating chile peppers with up to 3 dS m^{-1} brackish water could be possible by maintaining appropriate leaching fractions to sustain chile pepper production in freshwater-scare areas, where brackish groundwater is the only available source of irrigation. The yield response curves showed that the yield reductions in the chile peppers irrigated with natural brackish water were lesser compared to those of NaCl-dominant solution studies. Low yield reductions could be related to significant Ca^{2+} concentrations in the brackish groundwater and RO concentrate. However, there is further need to investigate the effects of different Na^{+}/Ca^{2+} concentrations on plant physiology, water transport, ion content and transport, growth, nutrition, and yields for improving the salt tolerance of chile peppers.

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

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