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Maintaining Silage Corn Production Under Sodic Irrigation Water Conditions in a Semi-Arid Environment

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Abstract: The Zayandeh-Rud watershed of Iran has had water scarcity for decades, giving rise to pressures toward limiting water allocation for the agriculture sector. Marginal waters can be an alternative source for irrigated agriculture in water-scarce regions if adequately managed. One of the critical hazards for sustainable agriculture and the environment is the accumulated salinity–sodicity problem as a consequence of irrigating with unconventional waters. Applying additional water beyond the crop water requirement, known as leaching application, has been suggested as a solution to this problem. A physical model was built to investigate the effects of the severe sodicity and salinity conditions of irrigation water by creating 250 mm diameter soil columns (27 columns) filled with sandy clay loam soil. The severity of the irrigation water's sodicity (sodium adsorption ratios (SAR): 5.27, 16.56, and 28.57) and its interactions with various leaching fractions (0%, 15%, and 30%) on critical soil chemical characteristics and corn yield were studied. Implementing a 30% leaching fraction reduced the SAR and salinity in the soil's first layer (0–10 cm) when irrigating with saline–hyper-sodic water (SAR = 28.57 and ECiw = 9 dS/m). However, an elevated level of sodicity accumulation in the soil profile was observed, emphasizing the importance of adding calcium and magnesium amendments during the irrigation season. A noticeable increase in the efficiency of leaching applications in reducing accumulated salts and the sodicity level in the corn rootzone was detected with higher levels of irrigation water sodicity. The reduction in the accumulated salinity and sodium in the first soil layer due to implementing a 30% leaching fraction resulted in a 223.3% increase in the total biomass of silage corn. Applying a 30% leaching fraction also increased the corn biomass by 58% and 114.56% when irrigating with waters with 5.57 and 16.56 SAR values. The effectiveness of a 15% leaching fraction for enhancing the soil and crop conditions was significantly lower than that of the 30% leaching fraction. Nevertheless, in case of unavailability of sufficient water supply for irrigation purposes, applying a 15% leaching fraction could mitigate the consequences of sodic water irrigation. The results demonstrate that in the absence of the proper calcium amendments, the implementation of leaching management could still be effective in enhancing corn production under sodic water irrigation conditions.

Keywords: corn; irrigation water; leaching fraction; sodicity; salinity

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1. Introduction

Low, non-uniform distribution and inappropriate rainfall timing have made Iran one of the most arid and semi-arid countries in the world [1]. One of the most important watersheds located in the central part of Iran is the Zayandeh-Rud basin because of its vital role in agricultural, industrial, and environmental contributions to the region. Population growth and industrial and agricultural development, in combination with recent severe droughts, have created critical water stress conditions in this watershed [2]. Severe water shortages in the Zayandeh-Rud basin have caused this watershed to be one of the most complex basins in the central part of Iran. The main portion of its cultivated area relies on severely dwindling irrigation supplies [3,4]. Silage corn is among the high water-demanding crops that have been grown by producers in the Zayandeh-Rud basin [5,6]. The sustainability of silage corn production requires sufficient irrigation water supply. However, recent water scarcity conditions in the region has necessitated the implementation of novel management methods to maintain crop production [7,8]. Unconventional waters, such as saline waters and municipal and industrial wastewater, can be considered alternative sources of irrigation water in arid and semi-arid regions [9–14]. Using marginal-quality water as irrigation water has significant potential to alleviate the severity of water shortages in the region through the reduction of freshwater withdrawal from existing sources, including surface waters or groundwaters [15–17]. Nevertheless, the use of unconventional waters as irrigation water without proper management could have considerable negative consequences depending on the water quality, type of irrigation system, and soil and weather characteristics, which should be accurately assessed [18–21]. One of the critical consequential hazards that makes the use of unconventional waters complicated is the irrigation water's sodicity, which can have severed negative effects on soil conditions. Sodicity refers to the unbalanced existence of excessive sodium ions in irrigation water in relation to calcium and magnesium. When sodic water enters soil, it interacts with the exchange sites on clay and organic matter surfaces. The relatively high accumulation of the sodium ions on the soil complex (exchange sites) can disintegrate the bond between soil particles and cause a significant reduction in soil water movement [22]. The slow soil water flow leads to a low infiltration rate, water ponding on the soil surface, poor drainage, and unfavorable soil aeration [23,24]. All these factors could result in a considerable reduction in crop yield and jeopardize the future of the agricultural economy in arid and semi-arid regions.

Yin et al. [25] introduced a coupled dynamic soil water content salinity and sodicity model to reveal the effects of crop tolerance to salinity on regulating the soil salinity and sodicity conditions and saturated hydraulic conductivity. They emphasized the vital role of understanding the crop tolerance to salinity and alkalinity (sodicity) in evaluating the sustainability of agricultural practices and environmental protection initiatives.

In a long-term study conducted by Choudhary et al. [26], the applicability of organic manure and crop residue as soil amendments was tested to mitigate the detrimental effects of irrigation with sodic waters. The experiments were carried out in sandy loam soil under wheat and rice cultivations. The researchers indicated that both organic materials were effective in enhancing the soil infiltration rate, mobilizing calcium (Ca^{2+}), and lowering the soil pH and exchangeable sodium (ESP).

The changes in the soil chemical properties of a calcareous clay soil without vegetation cover were monitored when irrigating with two sodic waters with sodium adsorption ratios (SAR) of 20 and 40 in Haymana, Ankara, Turkey [27]. The outputs of the research showed a slight increase in the dissolution of $CaCO_3{}^{2-}$ as a consequence of its interaction with the irrigation water, which ameliorated the negative effects of the sodium introduced by the irrigation water into the soil by replacing the adsorbed Na^+ with Ca^{2+}. They declared that the participated calcium carbonate could be used as long-term source of calcium in cases where agricultural soils are exposed to irrigation water sodicity.

A reduction in sunflower yield and a buildup of sodium in sandy loam soil as a result of irrigation with sodic water alternating with canal water was reported by Choudhary et al. [28]. The increases in the soil pH and exchangeable sodium were found to be directly related to the number of irrigations with sodic water in the cyclic application of canal water and sodic water under sunflower cultivation.

One of the management methods for controlling the adverse effects of irrigation water salinity and sodicity is the application of leaching water [29–31]. Leaching is defined as applying more water than the crop water requirement of the field during the growing season. The leaching water can transfer a portion of accumulated salts in the crop root zone through a deep percolation process. When leaching water is considered part of the irrigation depth for each irrigation event, the amount of leaching water is known as the leaching fraction [23]. The focus of most of the leaching management studies has been on controlling the salinity consequences of irrigation water or the reclamation of saline soils. Yang et al. [20] showed the superiority of sprinkler systems over drip irrigation systems regarding leaching application efficiency. The results of a study on the interactions of irrigation water salinity and the leaching fractions in hot pepper plants revealed that the effectiveness of the leaching fractions on salinity reduction varied depending on the crop growth stage [32]. Mostafazadeh-Fard et al. [33] reported significant interaction effects of leaching fractions and irrigation water salinity on winter wheat. The focus of the majority of leaching management studies has been on controlling irrigation water salinity, and very few studies have investigated the advantages of applying leaching water when irrigating with sodic waters.

Our literature review indicates that there is a certain lack of information regarding the effectivity of leaching management on controlling the consequences of irrigation with sodic waters on soil sodicity and crop production, especially when the sodicity level of the irrigation water supply is elevated [34].

Oztürk et al. [35] investigated the effects of sodic water and the leaching velocity on the soil physical and hydraulic properties in calcareous soil. Their outputs indicated a significant reduction in the soil bulk density and porosity under sodic water leaching application. They found that the sodium in leaching water forced the calcium (Ca^{2+}) to be transported, which resulted in preserving soil aggregation in deeper soil layers. In their research, the existing calcium in the soil limited Na^{+} induction. They found that the impacts of leaching water velocity and the sodium content in irrigation water can be minimal due to the existing calcium in the soil.

Chaganti et al. [36] investigated the reclamation process of saline–sodic soil by applying moderately sodic municipal water and adding biochar and compost amendments. Noticeable improvements in soil aggregation happened under the compost amendment conditions. Furthermore, an increase in the soil saturated hydraulic conductivity was observed under the biochar and compost amendment application.

To date, multiple studies have declared the existence of sodicity and salinity issues in irrigation water supplies in the central part of Iran [33,37–39]. However, no robust study has investigated the consequences of using sodic waters for irrigating corn in this region, and there is limited information in the literature identifying the responses of silage corn to various ranges of irrigation water sodicity. Moreover, suitable management methods to alleviate the consequences of using these waters have not been explored in the region of our study, especially in the arid province of Isfahan. Therefore, the current ongoing water scarcity in the Zayandeh-Rud watershed necessitated a study with the aim of achieving the following objectives: (a) investigating the practicality of irrigation with sodic water for corn production; (b) exploring effectivity of leaching applications to control the side effects of irrigation with sodic waters for preserving silage corn yield in the region.

2. Materials and Methods

2.1. Physical Model Preparation

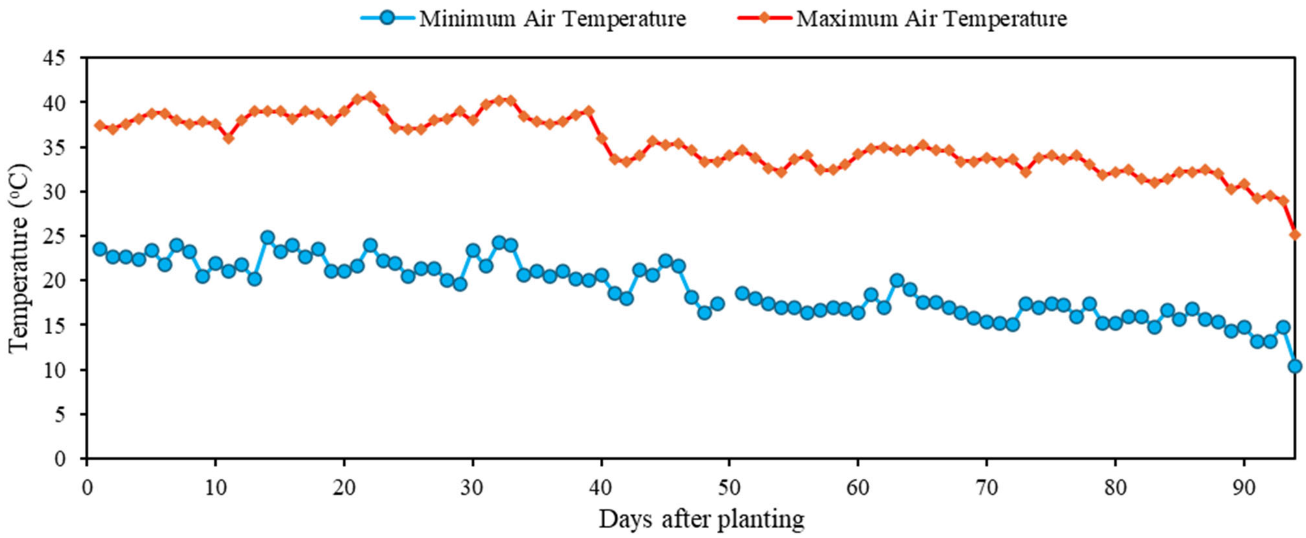
Isfahan province is located in the central part of Iran and covers a portion of the Zayandeh-Rud basin. Soil column experiments, representing physical models, were conducted at Isfahan University of Technology to simulate the soil and water conditions of the basin for corn production. Polyethylene columns with a 60 cm height and a 25 cm inner diameter were used. All columns were filled with soil material obtained from the soil profile up to a depth of 40 cm (Figure 1). The bottom 2 cm of the columns were filled with coarse gravel to facilitate the drainage process. About 20 cm were left on the top to allow for standing water during the infiltration activities.

Figure 1. The layout of the soil column experiments conducted in 2014 at the College of Agriculture, Isfahan University of Technology.

The sandy clay loam soil used to fill the columns was obtained from the Mahiar agricultural district located south of Isfahan province (latitude: 32°16′35.11″ N and longitude: 51°47′21.98″ E). The bulk density in each column was about 1.8 g cm^{-3}. The initial chemical and physical characteristics of the excavated soil are presented in Table 1. The weather conditions pertaining to the 2014 growing season are presented in Figure 2. As presented, only 3 mm of precipitation occurred during the growing season in 2014, which emphasizes the importance of seeking alternative water resources, such as unconventional waters, for irrigation purposes.

Table 1. The initial soil's physical and chemical properties [23].

Soil Physical Characteristics								
Sand		**Silt**		**Clay**		**Bulk Density (g/cm^3)**		**Soil Texture**
		(%)						
70		7		23		1.8		Sandy clay loam
Soil chemical characteristics								
EC (dS/m)	pH	NH_4^+ (mg/Kg)	NO_3^- (mg/Kg)	Ions (meq/L)			SAR	USSL classification
				Na^+	$Ca^{2+} + Mg^{2+}$	K^+		
2.13	8.5	84	165	9.62	9	2.20	3.2	Non-saline and non-sodic soil



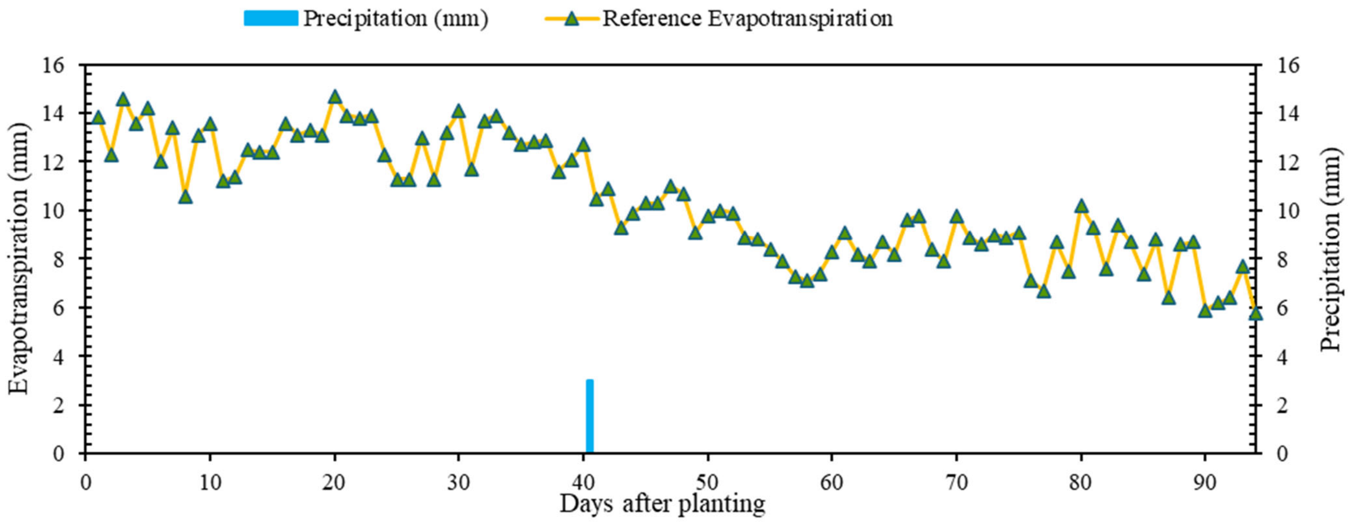


Figure 2. The weather characteristics of the experimental location during the 2014 growing season. The corn was planted on 7 July 2014.

Based on the chemical properties of the soil, it was categorized as non-saline and non-sodic soil. KSC 704 corn seeds were planted in the soil columns on 7 July 2014. Five silage corn seeds were initially sown, and the columns were irrigated with freshwater until the

V6 (six leaves) corn growth stage. At the four-leaf corn growth stage, the number of crops in each column was reduced to two, and the crop growth characteristics were monitored until the end of the growing season. Afterward, the corn was harvested on 8 October 2014, as the primary goal of planting the silage corn was to obtain biomass production. There was also an anticipated freeze in the region of the study in the upcoming days after the harvesting time, which forced us to harvest the corn before reaching full maturity.

2.2. Experimental Design

A factorial experiment based on a completely randomized plot design with 9 treatments (the interactions of three levels of irrigation water sodicity (SAR = 5.27, 16.56, and 28.57) with three leaching levels (0, 15, and 30%)) was conducted with three replications. The irrigation water sodicity levels were labeled S1, S2, and S3, respectively. The S2 treatment was created by blending S1 and S3 waters at a 1:1 ratio. The chemical properties of the irrigation waters used are presented in Table 2.

Table 2. Chemical properties of irrigation waters.

Irrigation Waters	pH	EC (dS/m)	SAR	K^+ (meq L^{-1})	Classification
S1	8.8	1	5.27	0.11	Non-saline or non-sodic
S2	8.76	4.7	16.56	0.53	Saline–sodic
S3	9.2	9	28.57	0.8	Saline–sodic

Moreover, leaching treatments were labeled LF_1, LF_2, and LF3, respectively. The leaching fraction is expressed as the ratio of the drained water depth to the depth of the irrigation water applied to the soils, and it can also be described as the ratio of the irrigation water salinity (EC_{iw}) to the salinity of the drained water (EC_{dw}), as follows [23]:

$$LF = \frac{D_{dw}}{D_{iw}} = \frac{EC_{iw}}{EC_{dw}} \quad (1)$$

where LF = leaching fraction, D_{dw} and D_{iw} = depth of the drainage water and irrigation water, respectively, and EC_{iw} and EC_{dw} = electrical conductivity of the irrigation and drainage water.

The treatments' implementation started when the seeds were at the four-leaf growth stage.

2.3. Irrigation and Field Management

Irrigation was applied following the depletion of 50% of the soil available water, based on the soil columns' weight reductions. All columns were weighed daily to determine the irrigation timing. Irrigation of the columns occurred when the water depletion in each column reached 50%. NPK (NUTRIX, Madrid, Spain) fertilizer with 20–20–20% nitrogen–phosphate–potassium was applied three times during the experiment at a 2 g L^{-1} concentration. The leaf area, stem diameter, height, and other plant components were measured three days before the harvesting time. All plants were cut at their base on the soil surface to measure the corn aboveground biomass. The plants were weighed after being dried in an oven for 72 h to determine the corn total aboveground biomass. The soil columns were carefully emptied to prevent the roots from being damaged. All roots were removed from the columns, and their volumes were recorded using the Archimedes method, based on changes in the water volume [40]. The root weight was not included in the total biomass determination. Soil sampling was simultaneously performed while emptying the soil columns and categorizing them by depths of 0–10, 10–25, and 25–40 cm. The soil samples were air-dried and passed through a 2 mm sieve. Afterward, a soil paste extract was obtained from each soil sample.

2.4. Measurements and Data Collection

The soil texture was determined using the hydrometer method. To determine the treatment effects on the soil salinity and electrical conductivity of the soil-saturated paste extract from each treatment, it was measured using the Ohaus Starter 3000C EC meter (Parsippany, NJ, USA). A METROHUM pH meter from Thomas Scientific (Swedesboro, NJ, USA) was used to measure the soil pH in the paste extract (pH in water). The sodium (Na^+) content was measured using a flame photometer (Buck Scientific, Ansonia, CT, USA), and the calcium (Ca^{2+}) and magnesium (Mg^{2+}) concentrations were determined using the titration method to calculate the sodium adsorption ratio (SAR) for analyzing the sodicity conditions of the soil affected by the experimental treatments and corn cultivation in the semi-arid region. The SAR was determined as follows [41]:

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

where Na^+, Ca^{2+}, and Mg^{2+} are the concentrations (meq/L) of sodium, calcium, and magnesium in the soil-saturated extract paste, respectively. The sodium concentrations were measured by a flame photometer, while the titration method was performed to measure the Ca^{2+} and Mg^{2+} concentrations in the saturated soil paste extract [42].

Irrigation water use efficiency (IWUE) was calculated as the ratio of the plant dry weight in each hectare to the amount of water applied during the irrigation season, which was calculated using the following relationship [43]:

$$IWUE = \frac{Y}{I} \quad (3)$$

where Y = yield (kg ha^{-1}), I = seasonal irrigation depth (mm), and Y is the corn total biomass (dry weight). This is because one of the main reasons for cultivating silage corn in the study region is to feed livestock plant aboveground biomass. Statistical analysis was carried out using the SAS 9.2 and Statistix 8.0 environments. To determine the statistical differences among the mean effects of the treatments on the soil chemical characteristics and corn yield, the LSD (least significant difference) and Duncan methods were carried out.

3. Results and Discussion

3.1. Soil Salinity (ECe)

As shown in Table 3, the effects of irrigation water salinity on the soil ECe were statistically significant. Increasing the irrigation water salinity caused a significant increase in the ECe, which was expected due to the considerable difference between the irrigation water salinity levels. The highest salinity accumulation was detected in the first soil layer (0–10 cm) when irrigating with S1 water. However, increasing the irrigation water sodicity level from 5.27 to 15.56 and 28.57 resulted in an accumulation of salinity in the deepest soil layer (20–40 cm).

Table 3. A comparison of the means of the ECe values affected by the experimental treatments–dS/m (p-value $\leq$ 0.05).

Depth	Irrigation Water Salinity			Leaching Fraction		
	S1	**S2**	**S3**	**LF1**	**LF2**	**LF3**
0–10 cm	2.07 c	3.46 b	6.09 a	4.57 a	3.92 ab	3.13 b
10–25 cm	1.78 c	3.94 b	5.77 a	3.68 a	3.86 a	3.94 a
25–40 cm	1.27 c	5.3 b	6.46 a	3.68 b	4.7 a	4.66 a

Note: The values followed by at least one of the same characters are not statistically different at a 5% probability level. S1, S2, and S3 are irrigation waters with SAR levels of 5.27, 16.56, and 28.57. LF1, LF2, and LF3 are 0%, 15%, and 30% leaching fractions.

These results are consistent with the findings of Amer [44]. The blending treatment (S2) significantly reduced the soil ECe compared to the S3 irrigation water treatment in all soil depths. Increasing the leaching level significantly reduced the soil ECe at the top 0–10 cm soil depth and increased the soil ECe at the lower 25–40 cm soil depth, which is consistent with the leaching effects reported by Ayers and Westcot [23]. The results of the interaction effects of the treatments on the soil salinity distribution are presented in Figure 3. As is clearly depicted, the leaching applications transported the accumulated salts to deeper soil layers and out of the crop root zone. The 30% leaching application reduced the accumulated salts at the 0–15 cm soil layer when irrigating with all sodic waters. However, increasing the leaching fraction from 15% to 30%was not effective in controlling the soil salinity conditions under saline–hyper-sodic irrigation conditions (S3). Therefore, applying 15% leaching would be a more reasonable choice when irrigating with waters with various sodicity levels (SAR from 5.27 to 28.57), due to the lower gross irrigation depth [45] compared to a 30% leaching application. The interaction results clearly demonstrate that the lowest level of irrigation water sodicity (SAR = 5.27) noticeably increased the soil salinity accumulation in such a way that the ECe values were above the corn salinity threshold [23]—(1.7 dS/m) in the entire corn root zone (0–40 cm) regardless of the leaching management treatments, except at the first soil layer (0–15 cm) under a 30% leaching fraction. Moreover, the increase in irrigation water SAR from 5.27 to 28.57 resulted in an increase in soil water salinity by 1.7-fold when no leaching was applied. This increase is expected to have been higher if the experiments were continued for more than one irrigation season. These findings were obtained under sandy clay loam soil with 23% clay content. Therefore, it would be reasonable to expect significantly higher levels of soil salinity accumulation in soil textures with higher clay content, which would increase the ion exchange area, and consequently, the adsorption of sodium.

3.2. SAR (Sodium Adsorption Ratio)

The results of the treatments effects on the soil SAR are shown in Table 4. The blending treatment (S2) significantly reduced the soil SAR compared to the S3 irrigation water treatment.

The 30% leaching application significantly reduced the soil SAR at a 0–10 cm depth (Figure 4), which indicates the effectiveness of the leaching application on the reduction of the soil SAR even without applying any calcium or magnesium amendments, which is similar to the results obtained by Chaganti et al. [46]. However, further soil SAR reduction should be considered to achieve success in agricultural systems. The elevated SAR values in the entire corn root zone noticeably affected the growing conditions of the corn and water advection in the soil profile. The high levels of SAR indicate that the soil aeration was limited during the growing season, which must have created unfavorable conditions for crop development. Excessive amounts of sodium in relation to calcium and magnesium suppressed the soil hydraulic conductivity by damaging the bonds between soil particles and causing clay swelling. The SAR distribution in the soil profile indicates that the sodium was accumulated in the first layer of the soil (0–10 cm), and solute transport was limited due to soil reduction due to excessive sodium. Observations during the 2014 growing season showed substantial restrictions in soil infiltration and deep percolation after the initiation of the third irrigation event with sodic waters (data are not presented). The sodium must have occupied the majority of exchange sites on the clay content [47]. Thus, water movement and solute transport was limited, which created a high SAR level at the first soil layer (0–15 cm) (Figure 4). This is similar to the results obtained by Mostafazadeh-fard et al. [48]. This phenomenon seems to be caused by the absence of essential amendments to replace the adsorbed sodium (Na^{+}) with calcium or magnesium. Therefore, it is highly recommended that in the presence of unbalanced sodium (a high SAR level) in irrigation water, the application of calcium and magnesium amendments or enhancing the soil organic matter should be considered. The calcium can replace the precipitated sodium over clay particles, and organic matter can provide soil organic carbon, which would facilitate solute transport and sodium leaching by providing additional exchange surfaces in the soil [46].

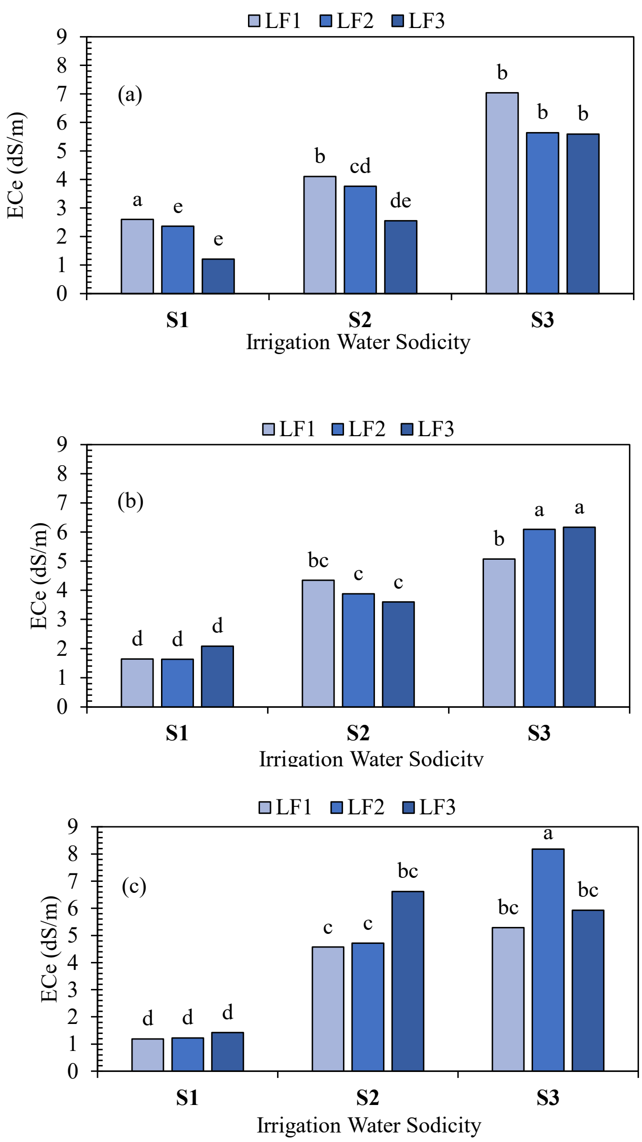


Figure 3. Interaction effects of the treatments on the soil ECe at (**a**) 0–10, (**b**) 10–25, and (**c**) 25–40 cm soil depths (p-value ≤ 0.05). S1, S2, and S3 are irrigation waters with SAR levels of 5.27, 16.56, and 28.57. LF1, LF2, and LF3 are 0%, 15%, and 30% leaching fractions. The values followed by at least one of the same characters are not statistically different at a 5% probability level.

Table 4. Comparison of the means of the soil SAR values as affected by the experimental treatments (p-value ≤ 0.05).

Depth	Irrigation Water Salinity/Sodicity			Leaching Fraction		
	S1	**S2**	**S3**	**LF1**	**LF2**	**LF3**
0–10 cm	6.09 c	20.83 b	37.92 a	25.16 a	21.75 ab	17.93 b
10–25 cm	2.94 b	8.98 a	13.34 a	9.35 a	7.34 a	8.57 a
25–40 cm	0.11 c	3.95 b	5.58 a	3.11 a	3.15 a	3.37 a

Note: The values followed by at least one of the same characters are not statistically different at a 5% probability level. S1, S2, and S3 are irrigation waters with SAR levels of 5.27, 16.56, and 28.57. LF1, LF2, and LF3 are 0%, 15%, and 30% leaching fractions.

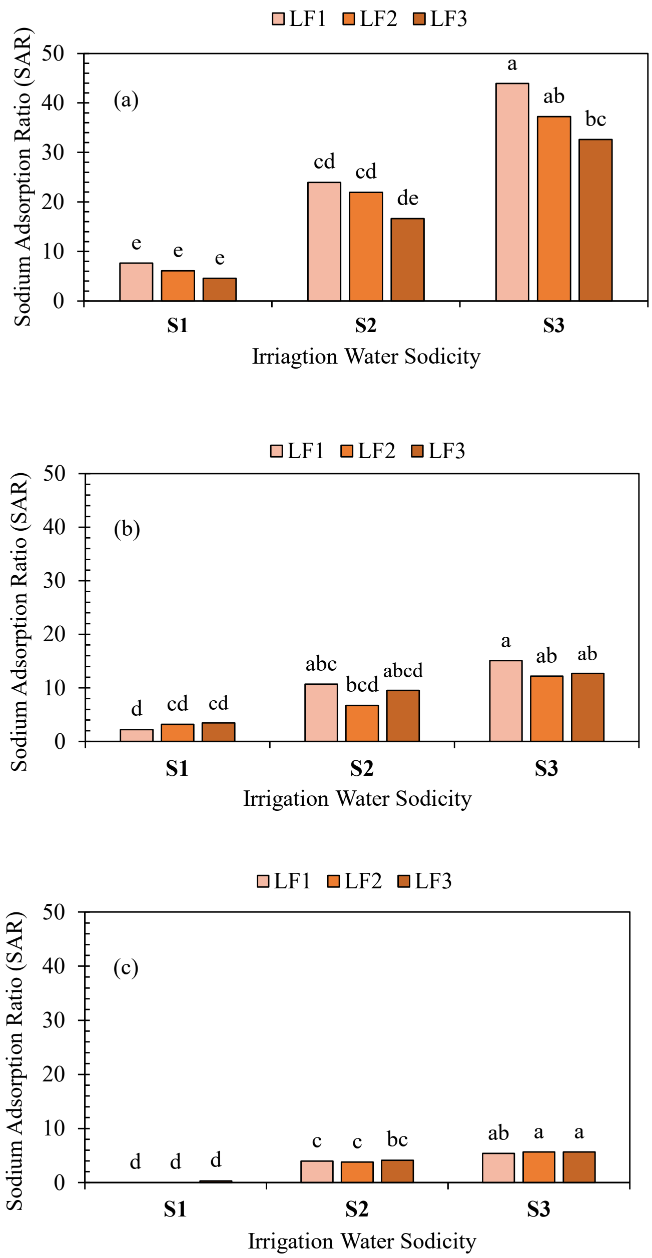


Figure 4. The interaction effects of the experimental treatments on the soil SAR at (**a**) 0–10, (**b**) 10–25, and (**c**) 25–40 cm soil depths. S1, S2, and S3 are irrigation waters with SAR levels of 5.27, 16.56, and 28.57. LF1, LF2, and LF3 are 0%, 15%, and 30% leaching fractions. The values followed by at least one of the same characters are not statistically different at a 5% probability level.

The sodium distribution pattern based on the interaction results indicates that sodium was accumulated in the upper levels of the soil no matter what leaching level was applied. Nevertheless, the 30% leaching fraction was more effective for SAR reduction under all three irrigation water conditions.

3.3. Soil pH

Soil pH is considered one of the most critical soil chemical properties as it can highly affect the availability of essential nutrients to crops. Moreover, soil alkalinity is expected to increase as a result of irrigation with sodic waters [49], which makes investigating soil pH crucial for sustainable crop production. As shown in Table 5, increasing the level of soil sodicity reduced the soil pH, but significant differences were only observed among the treatments effects for the 10–25 cm soil depth. At the 25–40 cm soil depth, significant differences were only observed between the impact of the S1 treatment and those of the S2 and S3 treatments. The leaching application had no significant effect on soil pH. Irrigation with sodic water instantly reduces the infiltration rate, and consequently, soil deep percolation; therefore, the salts introduced by the irrigation water accumulated in the first soil layer (0–10 cm), which considerably increased the soil ECe and SAR, and consequently, the soil pH. The obtained pH values under the S1 irrigation treatment indicate certain levels of solute transport occurrence under this condition, which resulted in altering the pH level at all three soil layers. This could be inferred from the higher level of pH at all three soil depths. It is worth pointing out that the initial soil pH was 8.5, which was not considerably different from the obtained values at the end of the experiments. Therefore, the pH of the alkaline soil was minimally effected by sodic water irrigation. Overall, the pH results reconfirm that calcium amendments (fertilizers) are vital when sodic water is the only choice for irrigation in the region.

Table 5. A comparison of the means of the soil pH as affected by the experimental treatments (p-value ≤ 0.05).

Depth	Irrigation Water Salinity			Leaching Fraction		
	S1	**S2**	**S3**	**LF1**	**LF2**	**LF3**
0–10 cm	8.73 a	8.82 a	8.65 a	8.71 ab	8.60 b	8.89 a
10–25 cm	8.81 a	8.59 b	8.39 c	8.53 a	8.68 a	8.58 a
25–40 cm	8.49 a	8.17 b	8.07 b	8.23 a	8.31 a	8.18 a

Note: The values followed by at least one of the same characters are not statistically different at a 5% probability level. S1, S2, and S3 are irrigation waters with SAR levels of 5.27, 16.56, and 28.57. LF1, LF2, and LF3 are 0%, 15%, and 30% leaching fractions.

3.4. K^+ (Potassium) Concentration

The concentration of K^+ in the irrigation waters was low, but the NPK fertilizer was applied three times during the growing season, and the initial soil potassium (K^+) concentration was 2.2 meq L^{-1}. Hence, the effects of the experimental treatments were analyzed as well. As shown in Table 6, the S1 treatment significantly reduced the soil potassium concentration in comparison with the S1 irrigation water treatment at the 10–25 and 25–40 cm soil depths, which was mainly because of the predominant sodium in the soil exchange capacity, which was introduced to the soil by the hyper-sodic irrigation water. The leaching fractions were not successful in changing the soil K^+, which could be due to the low potassium concentration in the irrigation waters.

Table 6. A comparison of the treatments' effects on the soil potassium concentration—meq L^{-1} (p-value $\leq$ 0.05).

Depth	Irrigation Water Salinity (Potassium Concentration)			Leaching Fraction		
	S1	S2	S3	LF1	LF2	LF3
0–10 cm	0.81 a	1.22 a	1.03 a	0.82 a	0.92 a	1.34 a
10–25 cm	0.82 b	0.90 ab	1.18 a	0.93 a	1.07 a	0.90 a
25–40 cm	0.53 b	1.06 a	1.07 a	0.87 a	0.90 a	0.90 a

Note: The values followed by at least one of the same characters are not statistically different at a 5% probability level. S1, S2, and S3 are irrigation waters with SAR levels of 5.27, 16.56, and 28.57. LF1, LF2, and LF3 are 0%, 15%, and 30% leaching fractions.

3.5. Total Biomass and Growth Components of Corn Maize

3.5.1. Corn Dry Weight (Total Aboveground Biomass)

As expected, increasing the irrigation water SAR level from 5.27 to 28.57 significantly reduced the corn dry weight (Table 7).

Table 7. A comparison of the treatments' effects on the corn maize yield and growth components (p-value $\leq$ 0.05).

	Irrigation Water Salinity			Leaching Fraction		
	S1	S2	S3	LF1	LF2	LF3
Total biomass—Dry Weight (g plant^{-1})	34.22 a	28.89 ab	19.89 b	26.00 a	27.89 a	29.11 a
IWUE (kg/ha.mm)	12.06 a	10.44 ab	7.03 b	10.16 a	10.00 a	9.37 a
Stem Diameter (mm)	15.48 a	13.66 b	12.90 b	13.56 a	14.25 a	14.24 a
Stem Height (cm)	56.70 a	39.11 b	39.55 b	36.77 c	43.04 b	55.55 a
Leaf Area (cm^2)	74.69 a	60.26 b	47.61 c	54.67 b	60.69 b	67.20 a
Root Volume (mm^3)	21.28 a	15.06 b	10.28 b	15.51 a	15.28 a	15.83 a

Note: The values followed by at least one of the same characters are not statistically different at a 5% probability level. S1, S2, and S3 are irrigation waters with SAR levels of 5.27, 16.56, and 28.57. LF1, LF2, and LF3 are the 0%, 15%, and 30% leaching fractions.

However, blending the water sources at a 1:1 ratio caused a 45.24% increase in the crop aboveground biomass. The results of the treatment interaction effects on the corn dry weight are presented in Figure 5. The results of the corn aboveground biomass indicate that the advantages of implementing leaching fractions significantly increase with increases in the irrigation water sodicity level, even though only the salinity and SAR conditions of the first layer of the soil were affected (Figures 3 and 4) by the application of the leaching fractions.

Applying a 30% leaching fraction resulted in a 223.3% increase in the crop total biomass when irrigating with the S1 water (SAR = 28.57). The increases in the corn biomass due to applying the 30% leaching fraction were 58% and 114.56% when irrigating with the S2 and S3 waters (SAR = 5.27 and 16.56). These findings emphasize the importance of leaching fraction application in enhancing corn growth conditions even without amendments. Applying a 15% leaching fraction was successful in improving the corn as well. Increases of 79% and 58% in corn biomass production were detected with a 15% leaching fraction while irrigating with the S2 and S3 irrigation waters (SAR = 16.56 and 28.57). Therefore, in locations where the water quality is degraded (water is sodic (SAR > 12)) and, at the same time, water quantity is limited, implementing 15% leaching could still be advantageous for enhancing corn production. Overall, the highest corn total biomass was detected when irrigating with S1 (SAR = 5.57) and applying a 30% leaching fraction, and the lowest biomass was found when irrigating with hyper-sodic water (SAR = 28.57) without applying any leaching fractions. Furthermore, no significant difference was observed between the corn total biomass obtained under irrigation with hyper-sodic water coupled with a 30% leaching fraction and the corn biomass obtained under non-saline/sodic water coupled with a 30% leaching application. These results prove the critical role of leaching application in preserving the sustainability of corn production under severe sodicity levels of irrigation water in a semi-arid region.

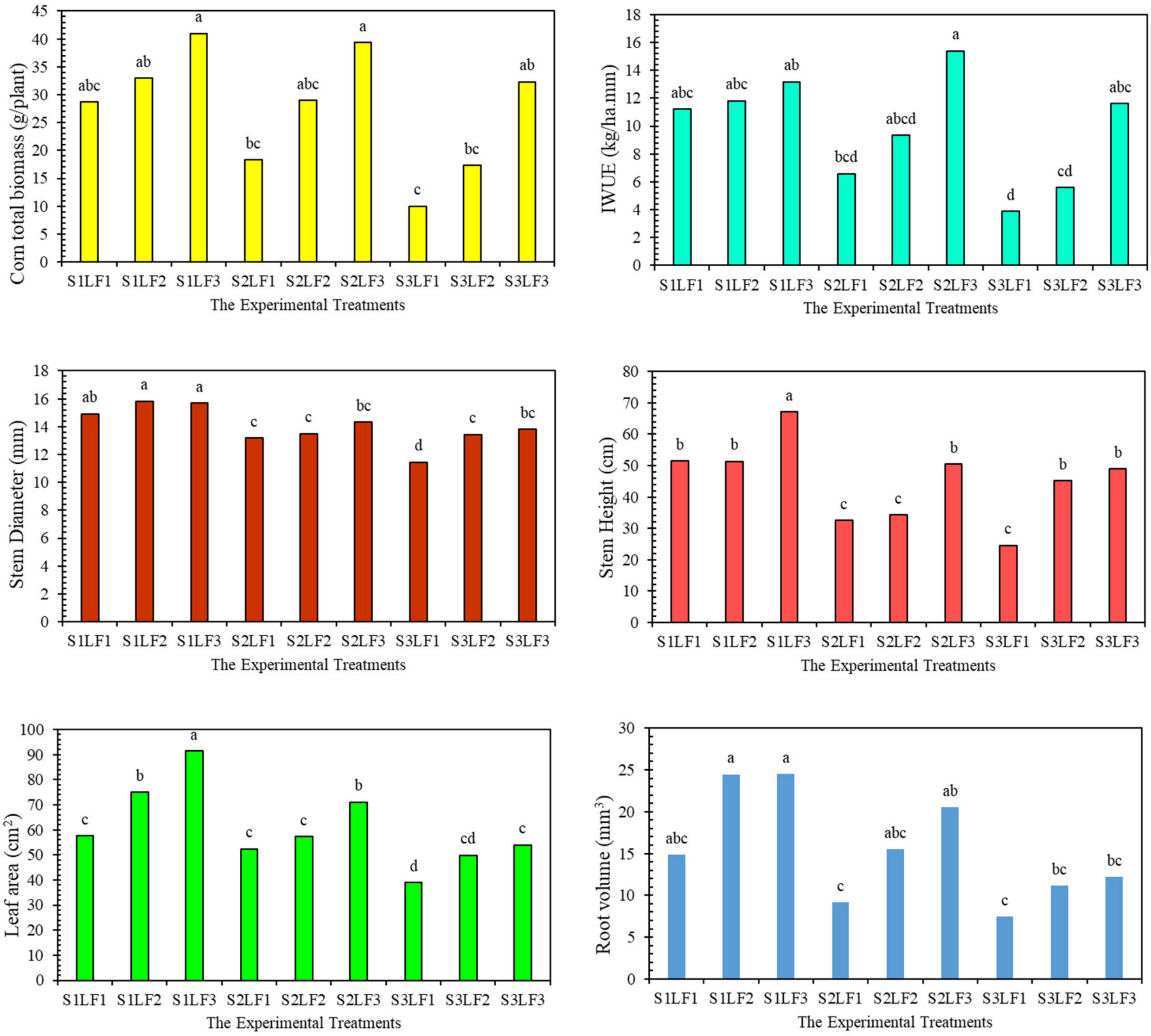


Figure 5. Comparison of the means of the corn biomass and growth components as affected by the interactions of the experimental treatments (p-value $\leq$ 0.05). The values followed by at least one of the same characters are not statistically different at a 5% probability level. S1, S2, and S3 are irrigation waters with SAR levels of 5.27, 16.56, and 28.57. LF1, LF2, and LF3 are the 0%, 15%, and 30% leaching fractions.

3.5.2. IWUE

As shown in Table 7, the blending treatment did not significantly increase the IWUE compared to the S1 treatment; also, there was no significant difference between the effects of the S3 and S2 treatments. The interaction effects of the experimental treatments (Figure 5) demonstrate that, similar to the corn biomass results, applying a 30% leaching fraction improved the corn irrigation water use efficiency when irrigating with sodic waters (S2 and S3). The IWUE was increased by 198.45% and 134% when irrigating with the S1 and S3 sodic waters when the 30% leaching fraction was imposed. Furthermore, implementing a 15% leaching fraction caused, on average, a 42.5% increase in the IWUE when irrigating with sodic waters (SAR_{S2} = 16.56 and SAR_{S3} = 28.57). No significant effect of applying leaching fractions on corn IWUE was detected for the irrigation with non-saline or sodic water (S1). The results also indicate that using 30% leaching when irrigating with saline hyper-sodic water resulted in an IWUE that was not statistically different from the one obtained under irrigation with non-saline and sodic water. The S2LF3 was found to be the most beneficial treatment, as its corresponding IWUE values were higher than those of the other treatments. There is likely a threshold of the irrigation water sodicity level that would limit the benefits of applying a leaching fraction without considering any calcium or magnesium amendments. Therefore, we recommend that numerical models, such as HYDRUS-1D [50], be calibrated and validated to explore wide ranges of irrigation water sodicity, which would eventually identify the threshold for maximizing the benefits of applying leaching fractions.

3.5.3. Stem Diameter

The variability in stem diameter values indicates that the stem diameter could be a valid index to track the effects of salinity and sodicity on corn production (Table 7). The blended treatment (S2) did not significantly increase the corn stem diameters compared to the S1 treatment. In addition, the application of a leaching fraction (15 and 30% leaching) did not significantly affect the corn stem diameters. The results of the treatments' interaction effects on the plant stem diameters are presented in Figure 5. The results show that only when irrigating with saline–hyper-sodic water (S3), the 15 and 30% leaching applications significantly increased the stem diameter. However, their effects were not significant in comparison with each other. Stem diameter measurement is among the most cost-effective methods to evaluate corn performance under different water quality conditions. However, the most meaningful comparison for corn producers would be the total biomass and grain yield values depending on the corn variety and their farming goals. Therefore, in this study, a linear correlation with an acceptable coefficient of determination ($R^2 > 0.6$) was determined between the corn biomass and stem diameter (Figure 6). This correlation was established to provide a fair estimation of the corn forage total biomass under various irrigation water sodicity levels and leaching management practices based on simple stem diameter measurements.

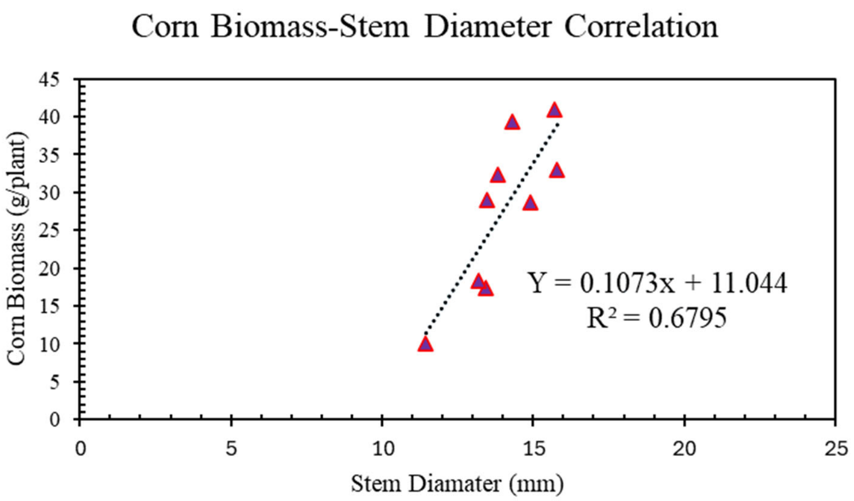


Figure 6. The correlation between the corn stem diameter and the total aboveground biomass under different irrigation water sodicity conditions and leaching fractions.

3.5.4. Stem Height

The results of the treatment's effects on stem height (Table 7) show that the blending treatment (S2) did not have a significant effect on the corn stem height compared to the S_1 treatment. The highest value belonged to the S2 irrigation water treatment. The 15 and 30% leaching applications significantly increased the corn stem height by about 17 and 51%, respectively. Based on the interaction results (Figure 5), applying a 30% leaching fraction when irrigating with the S1 water (SAR = 5.27, ECiw = 1 dS/m) resulted in the highest corn height compared to the other treatments. Implementing leaching management increased the corn height when irrigating with sodic water (S2 and S3). The corn height was significantly increased by applying a 15% leaching fraction when irrigating with saline–hyper-sodic water. However, using 30% leaching did not result in a significant corn height difference compared to the 15% leaching fraction. Applying the 15% leaching fraction was not effective for increasing the corn height when irrigating with the S1 and S3 waters, but the application of the 30% leaching fraction significantly increased the corn height. Therefore, additional experiments must be carried out in future studies to dig more into the responses of corn height to irrigation water sodicity levels. There might be a threshold of the irrigation water sodicity level that could trigger the effectiveness of a leaching application in the absence of calcium fertilizer. Overall, it is clear that the corn height was responsive to the leaching treatments. However, in this current study, we could not introduce corn height as a reliable index for analyzing the effects of sodicity management without calcium or magnesium application.

3.5.5. Leaf Area

The blended treatment (S2) significantly increased the corn leaf area (Table 7) compared to irrigation with S1 irrigation. The 15 and 30% leaching applications increased the corn leaf area, but only the 30% leaching effect was significant. Monitoring crops' leaf area to determine the leaf area index (LAI) or crop canopy cover (CC) growth is crucial, as it is the primary factor in understanding the effects of management treatments on crop growth and finding the crop stress level that could affect its transpiration. In this study, the leaf area of the corn around the ear was measured to find out if the experimental treatments had any impact on the corn leaf area. The high importance of corn leaves around the ear [51] was the reason for this selection. As is shown in Figure 5, the leaf area of the corn ranged from 39.03 to 91.50 cm^2. The application of a 15% leaching fraction did not statistically affect the corn leaf area when irrigating with sodic waters. The interaction results (Figure 5) reveal the superiority of the 30% leaching implementation on expanding the corn leaf area when irrigating with the three waters (S1, S2, and S3). The highest corn leaf area was found for the application of 30% leaching under the S2 irrigation water condition, and the lowest value was detected under the S3 irrigation without leaching application. The corn leaf area increased by 38% and 35.5% when irrigating with the S2 and S3 sodic water, respectively, when the 30% leaching fraction was implemented. However, a higher 58% increase in the leaf area was observed with the application of 30% (LF3) under the S1 (non-saline and non-sodic) irrigation water. Overall, to alleviate the consequences of irrigation water sodicity, applying a 30% leaching fraction in addition to the corn water requirement can be recommended.

3.5.6. Root Volume

The roots are a good indicator of crop establishment, especially under various stress conditions, including water, salinity, and heat stresses [5,52]. Hence, in the current study, the volume of the corn roots under various irrigation treatments was compared accordingly. A higher corn root volume was detected (Table 7) when irrigating with the S3 mixed sodic water compared to irrigation with the S1 treatment, but its effect was not statistically significant. The results of the interaction effects of the treatments on the plant root volume are presented in Figure 5. The results show that the application of the 30% leaching significantly increased the root volume, by 162.2%, when irrigating with the S2 (SAR = 16.56) irrigation water. Implementing the 30% leaching fraction also resulted in a 62% increase in the corn root volume when irrigating with the saline–hyper-sodic water. Moreover, applying 15% leaching fraction expanded the volume of the corn root by 49.3% and 69.13% when irrigating with the S1 and S3 sodic waters. Therefore, it can be inferred that the leaching fraction was able to facilitate corn root expansion when irrigating with sodic waters, which is a vital indicator of crop establishment.

3.5.7. Experimental Constraints and Future Studies

Performing experiments in cylindrical lysimeters, also known as soil columns, is highly valuable; however, these experiments can limit the generalization of the results obtained in this study to certain conditions that producers of corn face. The type of irrigation system, soil textures with higher levels of clay content, and the prevailing wind status in the region might need to be considered before generalizing the results to other conditions. Moreover, the main goal of this study was to maintain the silage corn yield under sodic irrigation conditions. However, further analysis would be beneficial if the duration of the experiments was extended and the grain yield was analyzed as well. To gain further insight into the effects of sodic water on corn productivity in semi-arid regions, we strongly recommend pursuing the goals of this study at the field scale under pressurized irrigation systems, such as sprinkle and drip irrigation systems, as the water and ion redistribution could be different due to their wetting patterns.

4. Conclusions

Water scarcity is a critical issue threatening sustainability of the agricultural industry in the Zayandeh-Rud basin, located in central part of Iran. Utilizing unconventional waters as irrigation water in combination with proper management could be considered as an alternative solution for dealing with water shortages. Cylindrical lysimeters (soil columns) were built to conduct soil and water quality experiments to seek solutions that could maintain silage corn production under non-convenient water-quality conditions. The impacts of several leaching applications when irrigating with sodic waters with various SAR levels were tested on the soil chemical properties and silage corn production. The results show that the 15 and 30% leaching applications significantly affected the ECe when irrigating with water with an SAR of 28.57. The effectiveness of leaching management in enhancing soil sodicity conditions increased with the severity of the irrigation water sodicity. However, this fact was not true for controlling the consequential soil salinity conditions. Increasing the leaching fraction from 15% to 30% did not have a considerable impact on the soil ECe. Therefore, pursuing a 15% leaching fraction was sufficient for controlling the soil salinity conditions. Depending on the salinity or sodicity level of the irrigation water, different corn responses were detected. The findings of this study reveal that the application of leaching fractions, even without additional amendments, can still enhance corn production. A higher silage corn biomass was found when irrigating with sodic water with a 16.56 SAR level combined with a 30% leaching fraction compared to when no leaching was applied when irrigating with water with a 5.27 SAR level. The results of this study lead to the conclusion that in areas similar to the Zayandeh-Rud basin of Isfahan that face severe water scarcity and where the allocation of convenient water resources is highly limited, it is feasible to use saline–sodic waters as irrigation water for silage corn production if it is accompanied by a 30% leaching fraction during the irrigation events.

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