Dryland Soil Research, Vol. 1, No. 2, pp. 77-91, 2025
Type of article: Original, Available online at www.dlsr.iut.ac.ir,
https://doi.org/10.47176/dlsr.01.02.1039

Characterization and management of salt affected soils in irrigated pistachio orchards (A case study: Ardakan, Yazd province)

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(Received 30 April 2025, Accepted 29 June 2025)

ABSTRACT

This paper categorizes the salt-affected soils into three major groups: saline, saline-sodic, and magnesium-affected soils. It discusses practical management strategies tailored to local conditions and offers recommendations to enhance agricultural productivity on these soils. For saline soils, the paper examines field-based approaches for managing the leaching fraction, compares actual with theoretical leaching requirements, and explores methods for improving leaching efficiency and maintaining root zone salinity within some acceptable limits. For saline-sodic soils, the role of salinity along with potassium and magnesium concentrations in assessing the risk of structural degradation is highlighted. Regarding magnesium hazards, evidence is presented showing an increasing trend of magnesium concentrations in Iran's soil and water resources. For this purpose, the chemical analysis of 135 water samples and 54 soil samples collected from 18 points in 3 depths of Ardakan pistachio orchards were used for interpretation of these resource characteristics. Water samples include all well waters used for pistachio irrigation and the location and density of soil samples were determined using Latin Hypercube Sampling strategy. Based on the results more than 75 percent of water samples had the salinity of more than 8.5 dS/m and more than the threshold salinity tolerance for pistachio and 25 percent of the samples have the salinities higher than 14.3 dS/m which is quite high for pistachio production. Findings indicate that salt accumulation due to irrigation with brackish and saline waters is the primary factor behind yield declines in irrigated agriculture, emphasizing the critical need for adequate leaching practices. While regarding to the sodium hazards all samples located in the region of no infiltration rate decrease and this hazard appears to be relatively limited , magnesium and alkalinity risks are emerging, particularly with the expanded use of nontraditional water sources such as treated wastewater and drainage water. Effective management of field salinity requires continuous monitoring of soil salinity status and leaching fractions across irrigation events, for which the use of simple tools like wetting front detectors is recommended. Reclamation of sodic and saline-sodic soils can be achieved through biological and chemical amendments, while leaching remains the key strategy for managing saline soils. Additional farm-level practices include applying mulches to curb capillary rise and evaporation, improving drainage efficiency, reducing saline water use in irrigation, and cultivating salt-tolerant or halophytic crops.

Keywords: leaching, Magnesium Hazard, Salinity Hazard, Sodium Hazard, Soil remediation.

1. Introduction

A major contribution to agricultural products in Iran with dry climate are irrigated lands and most of it with salt affected soils (SAS). The irrigation water resources are also increasingly salinizing. Improper application of these saline waters on soils accelerates soil salinization, too. Consistency in agricultural production on these SAS depends on making decisions and modifying the measures for their implementation. Obviously, the measures for management of different levels and kinds of salinity are not unique, and need to classify the group resources with somewhat similar management.

Different classification schemes are proposed for soil and water quality assessment regarding the salinity/sodicity problems, among them the (Wilcox 1955), (Richards 1954) and (Ayers and Westcot 1985) are the most popular. Some local classifications have also been proposed for countries such as India and Iran (Abedi Neirizi et al. 2002). These classifications rely on assumptions and prerequisites that restrict their utilization to a specific time or region. The validity of a part of these assumptions has been changed during the time or maybe remained valid on site-specific conditions (Asadi, Isazadeh et al. 2019) and their implementation for the current conditions of Iran is faced with the limitations, therefore it is necessary to revise them based on the current conditions in country.

Adventing of new chalenges and prospectives on utilization of SAS and water resources, also reveal the need of upgrading of the available classifications. Among many, the development of magnesium affected soil and water resources which is reported from Iran, Central Asia and Pakistan (Qadir, Schubert et al. 2018), development of desalination plants for agricultural purposes (Rahimi, Afzali et al. 2021), recycling of drain water in Haloculture (Haloculture refers to the sustainable production of agricultural and industrial products in saline environments) plans (Khorsandi, Siadati et al. 2020) and environmental/ non-agricultural use of saline soils and water resources (Salehi 2020) are examples of new features in implementation of these resources.

This paper reviews the status of Iran's agricultural soil and water resources regarding different categorization criteria . Different approaches, which are used or proposed for improved utilization of these resources in Iran, are reviewed at the end. The following describe the general criteria for soil and water quality categorization.

A. Salinity hazard

The most popular criteria for irrigation water salinity/ sodicity is Wilcox's diagram (Wilcox 1955), based on which water resources with salinity levels lower than 0.25 dS/m are considered as low salinity (C1), between 0.25 to 0.75 dS/m is considered as medium salinity (C2), between 0.75 to 2.25 dS/m as high salinity (C3) and more than 2.25 dS/m is considered as very high salinity (C4). This classification is based on the relationships between irrigation water and soil saturated extract's EC in which more than 1300 samples of surface and groundwater through western US is evaluated. Based on Wilcox's reports at that time, more than half of samples at that time had EC of lower than 0.75 dS/m and only 10 percent of samples had EC values higher than 2.25 dS/m.

Wilcox (1955) correctly relates soil salinity to irrigation water salinity and leaching fraction (LF) based on which he proposed a classification included 5 classes of lower than 2 to more than 16 dS/m. The suitability of these salinity classes for crop production ranges from being suitable for all crops at salinity levels below 2 dS/m, to being suitable only for a few salt-tolerant native forage crops at levels above 16 dS/m. The list of proper crops for these classes is extending due to the several research activities in recent decades.

Considering the steady state conditions and with assumptions, Ayers and Westcot (1985) showed that the mean root zone electrical conductivity (EC_e) is a function of irrigation water electrical conductivity (EC_{iw}) and a concentration factor (X) which is dependent on leaching fraction (LF) (Ayers and Westcot 1985):

$$EC_e \text{ (dS/m)} = X.\ EC_{iw} \text{ (dS/m)} \quad [1]$$

In this approach they proposed a lookup table for estimating the root zone salinity (X factor) based on leaching fraction (LF), suggesting that under 15–20% LF, root zone salinity is approximately 1.5 times the irrigation water salinity. These values reflected typical irrigation conditions in the U.S. at the time and were widely used in salinity response studies. In contrast, Wilcox's classification lacks a direct link between water and soil salinity classes. As a result, while the soil salinity thresholds seem reasonable, the water quality categories are overly conservative. For instance, C3 water (classified as saline) corresponds to a root zone salinity of around 4 dS/m, which is still suitable for most crops except salt-sensitive species.

Further revisions of this classification (Fipps 2003) and (Abedi Neirizi et al. 2002) have increased the level of water salinities which are not applicable in agriculture by 3 and 6 dS/m respectively. The Indian classification of water salinity also incorporates rainfall, salinity tolerance of crop and clay content of soil (Minhas 1996) based on which the range of water salinity that is suitable for tolerant crops is extended compared to the Wilcox's diagram. Along with this table, recommendations for soil reclamation and the proper season for utilization of saline water in different crops are also included.

Regarding the situation of those days' agriculture sector in Iran, a new classification guideline was published in 1998 which is known as Neirizi's classification (Abedi Neirizi et al. 2002). In this classification, the effects of leaching fraction on the buildup/leaching of salts in soil is considered, based on which the LF value is assumed to be equal to 0.2 regarding the overall efficiency of irrigation systems in the country and mean root zone salinity is supposed to be 1.3 times of irrigation water salinity based on the concentration factor. For the LF values higher than 0.2 or in light textured soils, the range of each class for suitability of saline water will extend (Abedi Neirizi et al. 2002).

B. Sodium hazard

Extra sodium on the exchangeable sites of soils leads to dispersion of aggregates and as a result, the fine particles seal the intra- aggregates pores and soil infiltration rate decreases. Exchangeable sodium percent (ESP) is used for evaluation of sodium hazard in soil.

$$ESP(\%) = \frac{Na_{ex}(cmol/Kg)}{CEC(cmol/Kg)} \times 100 \quad [2]$$

In which Na_{ex} is exchangeable sodium and CEC is cation exchange capacity of soil. As the laboratories procedure for measurement of both CEC and Na_{ex} is along with different error sources, an experimental relationship is proposed to calculate ESP from sodium adsorption ratio (SAR) of irrigation water:

$$ESP = \frac{100(-0.0126 + 0.01475SAR)}{1 + (-0.0126 + 0.01475SAR)} \quad [3]$$

$$SAR = \frac{Na^{+}}{\sqrt{\frac{Ca^{2+} + Mg^{2+}}{2}}} \quad [4]$$

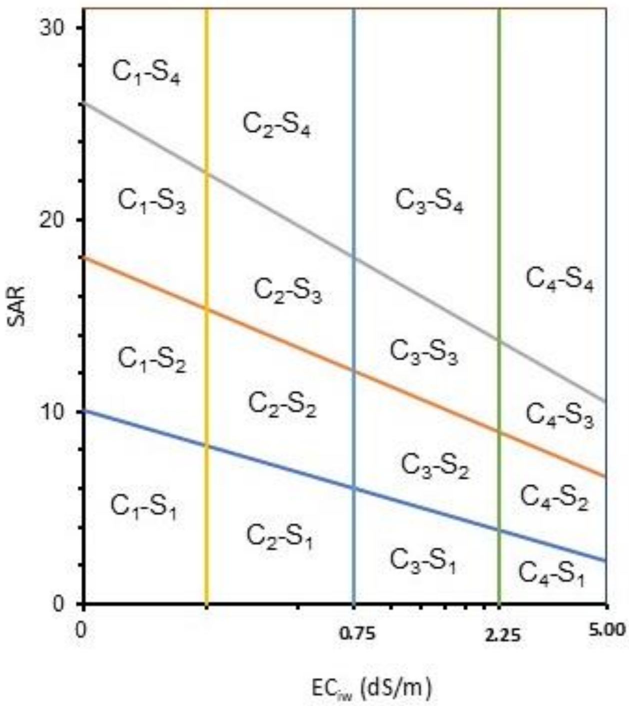

Figure 1. Wilcox's diagram for classification of salinity and sodicity hazard in irrigation water

In which Na^+, Ca^{2+} and Mg^{2+} are the concentrations of Sodium, Calcium and Magnesium of irrigation water in meq/L. Using experimental equation (3) which is derived from Gappon's coefficients for exchange of univalent and divalent cations on exchangeable sites, the ESP of soil is estimated based on SAR of irrigation water in equilibrium with soil. Classification of SAR levels has been also proposed by Wilcox in 1955 in a manner similar to that of salinity in which SAR levels between 0 and 10 are classified as low (S1), 10 to 18 as medium (S2), 18 to 28 as high (S3) and higher than 26 as very high (S4). He also combined the classifications for EC levels (C1 to C4) and SAR levels (S1 to S4) and proposed a 16 categories diagram for irrigation water classification, as is shown in Figure 1.

Increasing the salinity of soil solution has a positive effect on soil aggregation. On the higher salinities of soil solution, the Diffused Double Layer's (DDL) thickness is decreased and, as a result, the adhesive forces between clay particles dominates and leads to structural stability (Quirk and Schofield 1955). Changes in the DDL thickness even in the Angstrom scale is a type of swelling (Bennett, Marchuk et al. 2019). Therefore, the effect of salinity on DDL thickness is a determinant factor in pores geometry and, as a result, in hydraulic conductivity. In this way, sodium hazard should be evaluated along with salinity hazard. Figure 2 illustrates the dual effects of salinity/sodicity on reduction of infiltration rate as a result of soil dispersion (Ayers and Westcot, 1985). For higher salinity levels, Mohanavelu et al., (2021) introduced a curve shaped chart that included salinity levels up to 100 dS/m (Mohanavelu, Naganna et al. 2021).

In calcareous soils, the Ca concentration in equilibrium with solid CaCO3 phase Ca_{eq} could be estimated from the following relation (Suarez 1981):

$$Ca_{eq}=X\times(P_{CO2})^{1/3} \quad [5]$$

in which X is a factor and P_{CO2} is the partial pressure of carbon dioxide gas in the soil air. He proposed a lookup table to extract X factor and P_{CO2} could be considered as 0.0007 atm for the top layers of soils. (Lesch and Suarez 2009) proposed an algebraic relationship to estimate X as it could be used in spreadsheets. The calculated Ca_{eq} could be replaced in equation (4) to calculate adjusted SAR (SAR_{adj}):

$$SAR_{adj} = \frac{Na^+}{\sqrt{Ca_{eq}^{2+} + Mg^{2+} / 2}} \quad [6]$$

Recent research activities provide more evidence about the negative effects of both potassium and magnesium in addition to sodium on soil physical properties (Zhu, Ali et al. 2019, Liang, Rengasamy et al. 2021, Qadir, Sposito et al. 2021). Elevated potassium and magnesium concentrations are common in recycled wastewater resources (Oster, Sposito et al. 2016) which are increasingly used as irrigation water in agriculture, while their negative effects on soil infiltration, water quality and plant growth is reported by (Qadir, Schubert et al. 2018).

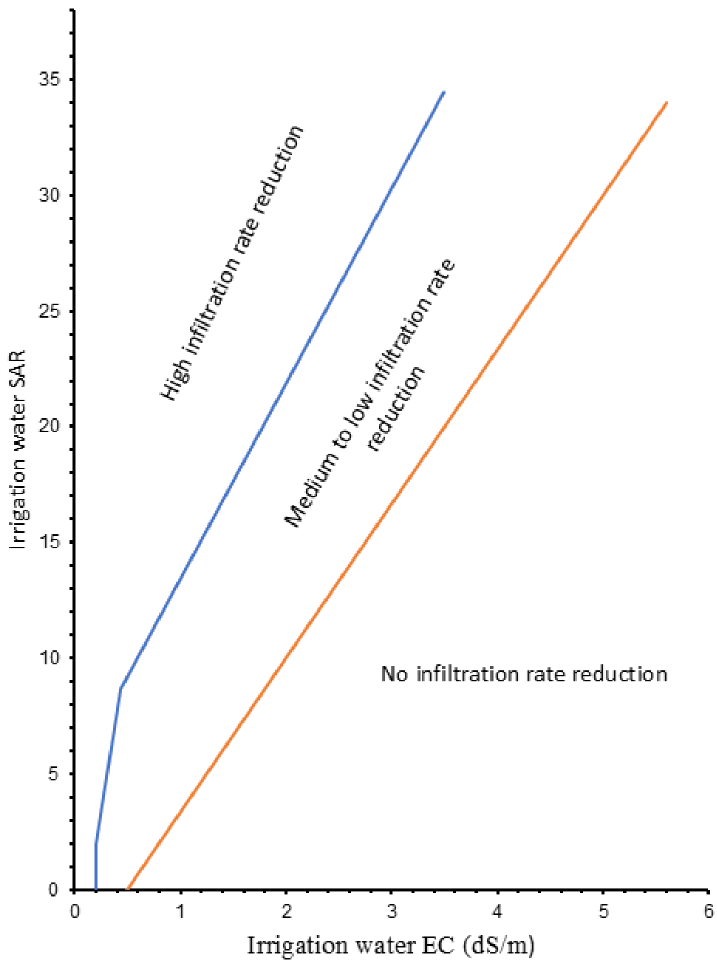

Figure 2. Guideline for evaluating the effects of salinity and sodicity on infiltration rate as proposed by (Ayers and Westcot 1985)

Cation Ratio of Structural Stability (CROSS) index was proposed by Australian researchers to evaluate the overall effects of these cations on soil structure and infiltration rate (Rengasamy and Marchuk 2011):

Figure 3, illustrates a graphical guideline same as Figure 2 for interpretation of CROSS index in relation to EC of irrigation water is proposed by Qadir et al., (2021). Using the error bars, we divided this graph into 3 areas of high to low risk of infiltration reduction.

$$CROSS = \frac{Na^{+} + 0.56K^{+}}{\sqrt{\frac{Ca^{2+} + 0.60Mg^{2+}}{2}}} \quad [7]$$

This index was then revised and optimized based on the dispersing power of cations (Smith, Oster et al. 2015) as follows:

$$CROSS_{opt} = \frac{Na^{+} + 0.335K^{+}}{\sqrt{\frac{Ca^{2+} + 0.0758Mg^{2+}}{2}}} \quad [8]$$

The CROSS index (Equations 7–8) provides an improved assessment of sodicity hazards over the traditional Sodium Adsorption Ratio (SAR), particularly under the calcareous soil conditions common in Iran. Unlike SAR, the CROSS index accounts for the different flocculation and dispersion effects of cations. It assumes that magnesium has a lower flocculating power than calcium, and that potassium can contribute to dispersion effects—both of which are important in sodicity development.

D. Magnesium hazard

Degradation effects of sodium is accelerated in magnesium affected soils or when irrigating with high Mg/Ca ratios in irrigation water. In this way, at a specified SAR level of irrigation water, with increasing Mg/Ca ratio, the soils with higher sodium will develop. The studies of Bekbaev et al., (2005) in southern Kazakhstan revealed that many irrigation water sources containing elevated levels of magnesium concentration and Mg/Ca ratios of lower than the unit. In more than 30 percent of soils irrigated with these types of water, the exchangeable magnesium percent reaches to more than 25-45 percent

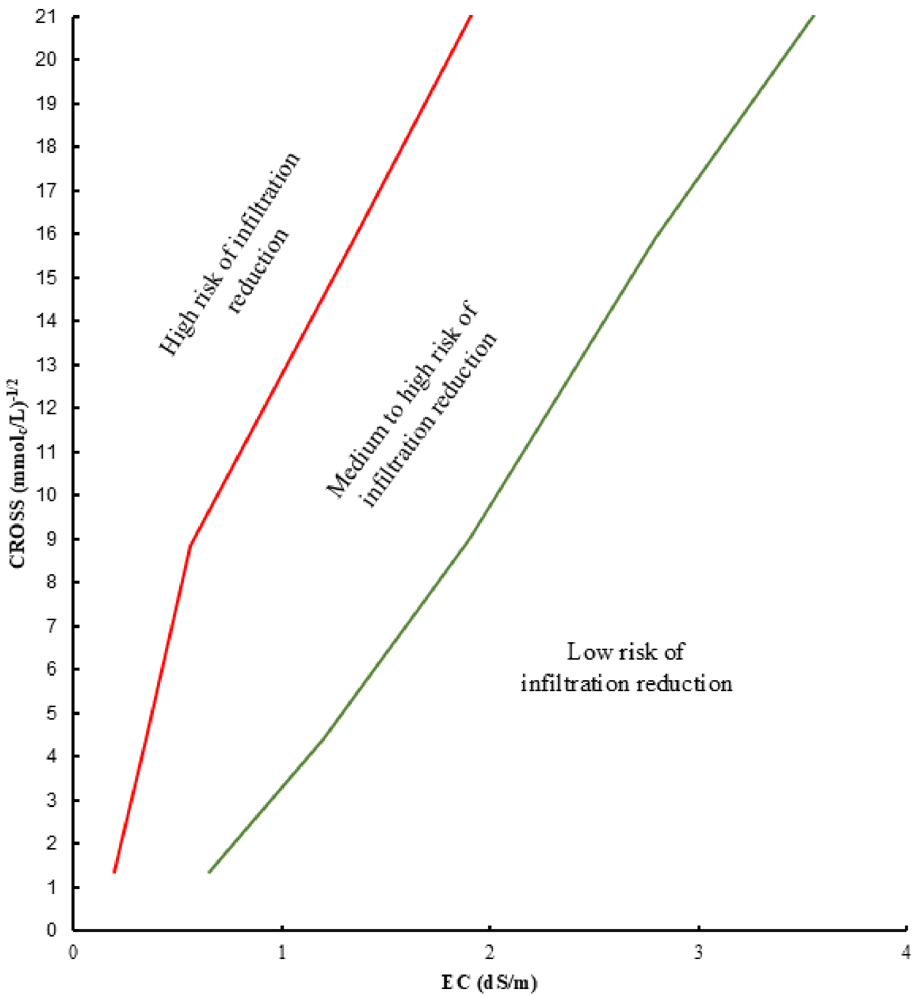

Figure 3. Guideline for interpretation of CROSS index at different EC levels. Modified from (Qadir, Sposito et al. 2021)

and in some cases up to 60 percent (Bekbaev, Vyshpolsky et al. 2005). These types of soils, which are known as Takyr have slow infiltration rates and low hydraulic conductivity. Another research by (Vyshpolsky, Qadir et al. 2008) on these lands showed that application of 4.5 ton/ha of phospho- gypsum reduced exchangeable magnesium percent by 31 percent and increased cotton yield.

High Mg/Ca levels are reported for irrigation water sources of Iran. As Dehghani et al., (2012) reported, about 55 percent of more than 6200 water samples had Mg/Ca ratios of more than unity (Dehghani, Malakouti et al. 2012). These levels of magnesium content in soil and water systems are also reported for Pakistan and the Central Asia (Qadir, Schubert et al. 2018). Dehghani et al., (2021) evaluated the effects of different irrigation water salinity and Ca/Mg ratios on the growth and performance of pistachio seedlings and reported that at each salinity level the highest growth and membrane stability was related to the treatment with Ca/Mg ratio of about unity (Dehghani, Rahnemaie et al. 2021). Except for these few examples, the adverse effects of this problem in agriculture sector is not addressed quantitatively (Qadir, Sposito et al. 2021) and needs to be considered in developing a country wide categorization and assessment.

C. Alkalinity hazard

Soils are called alkaline when their pH is higher than 7, while the pH levels between 7 to 8 do not impose specific limitations for most crops. Generally, soils with pH levels of more than 8 are considered as “alkaline soils” (Rengasamy, de Lacerda et al. 2022). Nutrient deficiency and ion toxicity occurs with higher intensities under alkaline conditions. The carbonates' alkalinity is responsible for high pH values in calcareous soils, which buffer the soil pH between 8 and 8.5.

Irrigation with river water sources that contain low sodium (SAR less than 9) along with the dominance of carbonates species leads to the development of alkaline - sodic soils (Rengasamy, de Lacerda et al. 2022). Jobbágy et al., (2017) estimated that the global coverage of soils

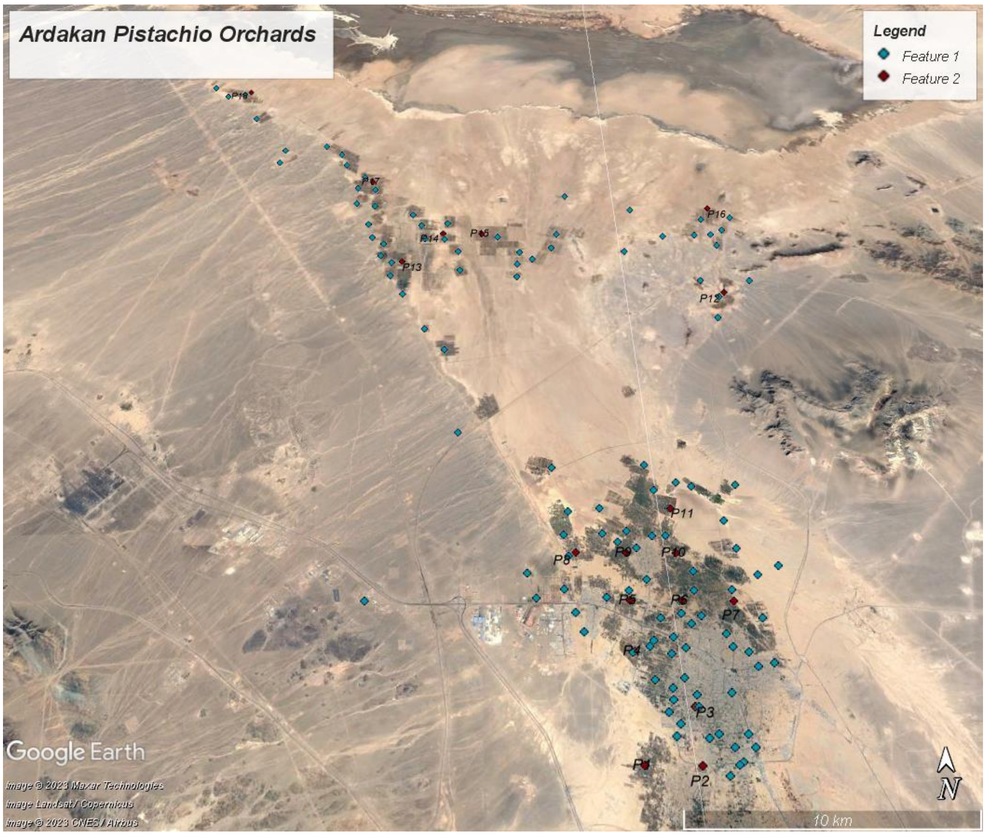

Figure 4. The location of studies soil and water samples

with pH higher than 9 is about 2.7 percent, but it's distribution under low slope lands (lower than 0.05 percent) in semiarid – semi humid regions is about 18 percent (Jobbágy, Tóth et al. 2017). Singh et al., (2022) developed a soil quality index (SQI) for soils irrigated with different levels of bicarbonate in irrigation water, in which soil pH, was the most important indicator and was highly correlated with some other variables (Singh, Kumar et al. 2022). Residual sodium carbonate (RSC) is another index of soil and water alkalinity which imposes negative effects on crop productivity for crops irrigated with groundwater resources having RSC of more than 3.5 meq/L (Bali, Singh et al. 2020).

2. Materials and Methods

This paper illustrates the situation of some saline agricultural water and soil resources regarding different classification schemes. Agriculture in the central plateau of Iran is fully dependent on irrigation, while secondary salinized soils in this part of the country are mainly irrigated with saline deep groundwater resources which are pumped to the surface and used for irrigation of salinity tolerant crops (Cheraghi, Hasheminejhad et al. 2007). Pistachio is the most widely cultivated crop, which is irrigated with these saline water resources and is replacing other salinity tolerant annual crops such as barley, sugar beet, cotton which were traditionally cultivated under saline conditions.

Pistachio orchards in the north of Ardakan city of Yazd province are the hotspots of irrigation with high salinity water resources. In this paper, 135 water samples which are used for irrigation of pistachio orchards in the North Ardakan area are evaluated in different classifications. Among these water samples, 18 fields were selected for which soil samples are augered down to 90 cm depth in 30 cm increments. The location and density of soil samples were determined using Latin Hypercube Sampling strategy (Minasny and McBratney, 2006). The situation of these samples in different soil classification schemes is also evaluated. Figure 4 shows the location of soil and water samples in the north Ardakan area of Yazd province. The samples were analyzed in the laboratory for the composition of soluble ions by methods described by Richards (1954).

For salinity hazard the status of fields leaching fraction (LF) is compared with a graph derived from equation (1) considering different X values at each LF (Ayers and Westcot, 1985). The sodicity hazard was evaluated using the SAR, CROSS and SAR_{adj} indices, the magnesium hazard was evaluated with Mg: Ca ratio and alkalinity hazard was evaluated with comparison of bicarbonate ion concentration with the its toxicity level. Also a guideline

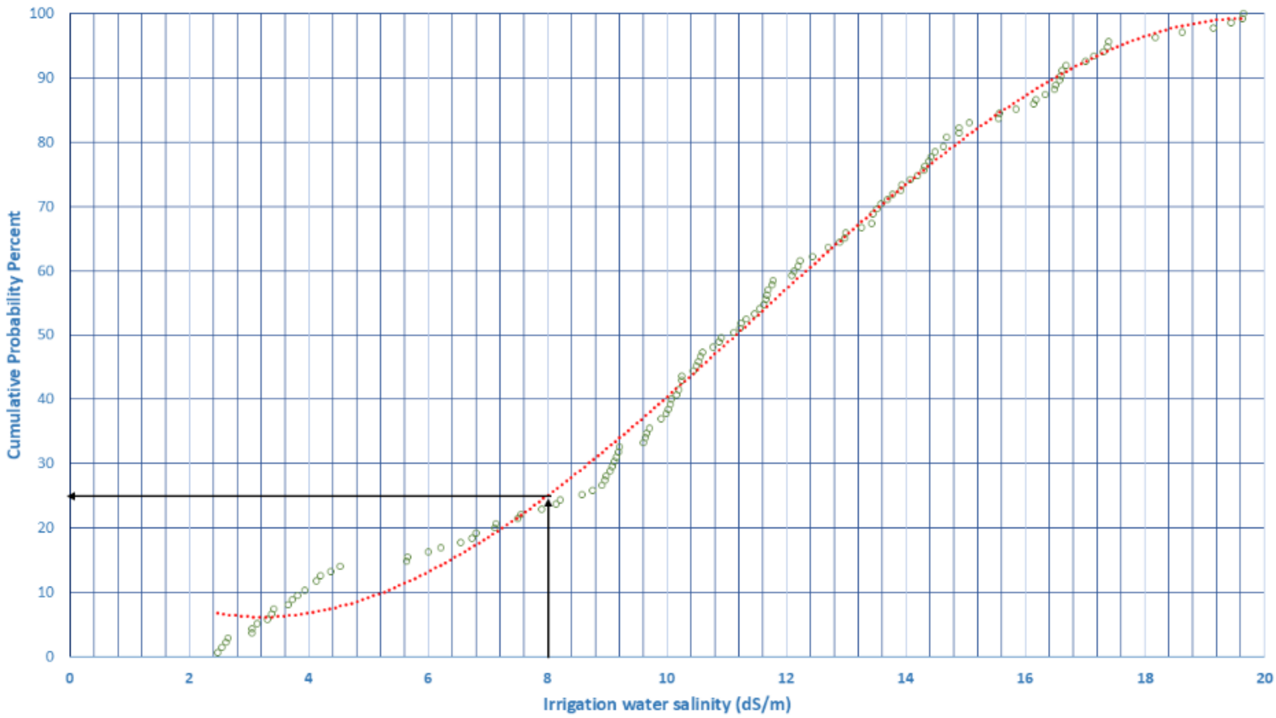

Figure 5. Distribution of irrigation water salinity in evaluated samples

for management practices for the salt affected soils of the study area is discussed.

3. Results and Discussion

3.1. Salinity buildup

Irrigation water sources have the salinity level ranges from 2.47 to 19.65 dS/m with an average of 10.97 dS/m. Based on the Figure 5, more than 75 percent of these well water sources had the salinity of more than 8.5 dS/m which is considered as the threshold salinity tolerance for pistachio and 25 percent of these resources have the salinities higher than 14.3 dS/m which is quite high for pistachio production.

To avoid the buildup of salinity in the root zone, leaching has to be considered in irrigation scheduling. The minimum required leaching to control root zone salinity within the tolerance of crop or leaching requirement (LR) could be calculated as follows:

$$LR = \frac{EC_w}{5(EC_e^*) - EC_w} \quad [9]$$

in which EC_w is the electrical conductivity of irrigation water (dS/m) and EC_e^* is the average soil salinity which is tolerated by crop as measured in saturated paste extract. As illustrated in Figure 6, about 50 percent of irrigated fields need LR values of higher than 22%.

As explained for equation (1) mean root zone salinity of soil could be calculated for each level of leaching by assuming LF=LR, while the measured soil salinity in most cases is lower than the calculated ones as is illustrated in Figure 7.

This discrepancy suggests that, in practice, farmers tend to apply leaching fractions (LF) higher than the minimum leaching requirement (LR), likely due to inefficient irrigation practices or attempts to manage salinity risk more conservatively. Consequently, the actual leaching leads to more salt removal from the root zone than predicted, resulting in lower observed salinity levels.

Beyond irrigation behavior, several soil-related factors may also contribute to the observed differences. For example, soil texture influences water movement and salt distribution: coarse-textured soils tend to allow deeper percolation and greater salt leaching, while finer-textured soils retain more salts. Precipitation events, especially during the off-season, can further dilute or flush salts, particularly in the upper soil layers, which may not be accounted for in steady-state models. Additionally,spatial heterogeneity in soil hydraulic properties, and crop uptake patterns may also play a role in reducing the observed salinity relative to the theoretical estimates.

Considering the precipitation of carbonates under low leaching fractions, the Watsuit model predicts lower mean root zone salinities (Hasheminejhad et al., 2013). As Shamsi et al., (2023) reported for the same area, there was stronger regression between measured and predicted values of Watsuit model compared to that of equation (1) (Shamsi et al., 2023).

The Watsuit model is a steady-state analytical model used to estimate root zone salinity under irrigation. Unlike

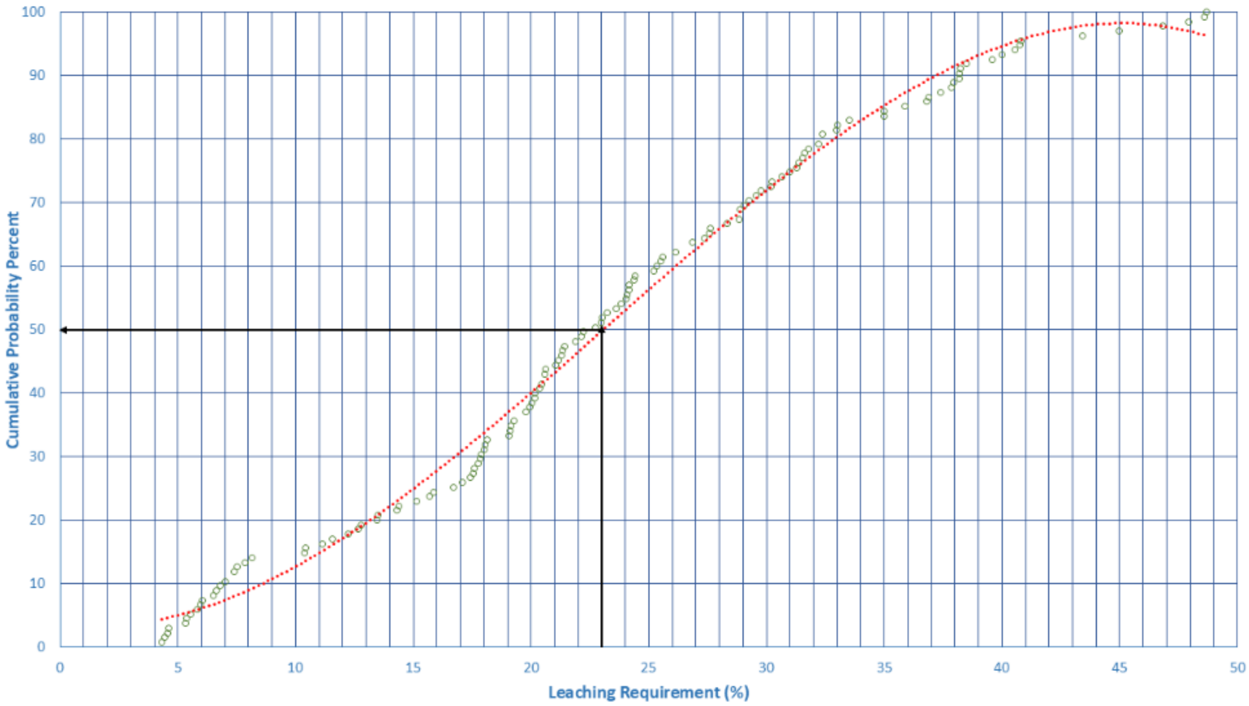

Figure 6. Distribution of leaching requirement (LR) in evaluated samples

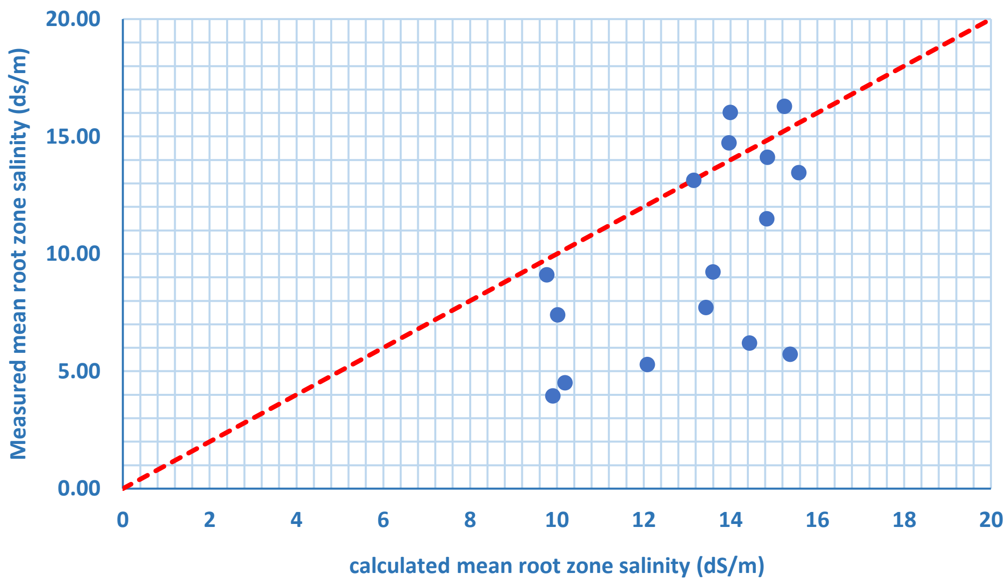

Figure 7. Relationship between measured and calculated mean root zone salinity

traditional models, Watsuit explicitly considers chemical reactions—especially precipitation and dissolution of salts like calcium carbonate—which are particularly important in calcareous soils. It incorporates the interactions between irrigation water composition, soil mineralogy, and solubility equilibria to more accurately estimate the electrical conductivity of the soil saturation extract (ECe) and the sodium adsorption ratio (SAR) in the root zone.

In contrast, the traditional leaching fraction method (equation 1) treats the system as a simple mass balance, assuming full solubility of salts and ignoring chemical equilibria and precipitation reactions. While this approach is easier to apply, it often overestimates salinity in calcareous soils where calcium precipitation reduces salt

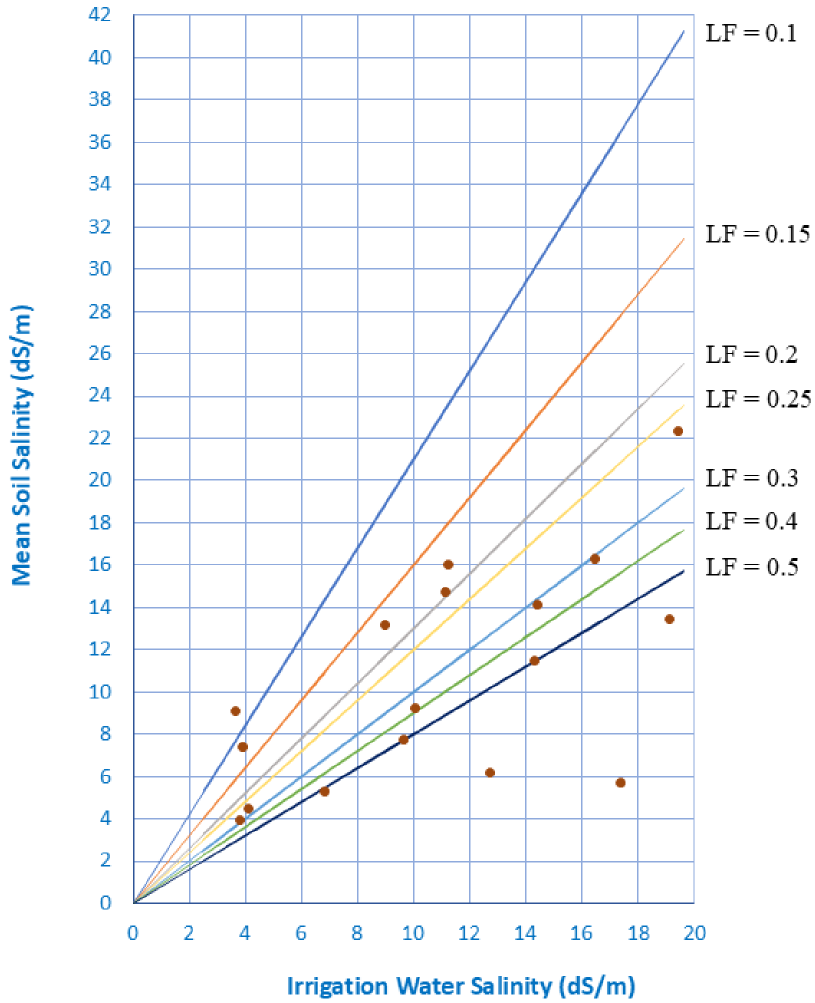

Figure 8. Distribution of irrigation water salinity and average soil salinity for 17 soil samples at different leaching fraction levels.

concentrations in the soil solution. Thus, Watsuit provides a more chemically realistic and reliable estimate of salinity and sodicity risks, especially under conditions where calcium dynamics significantly affect soil-water chemistry.

Farmers are generally used to apply high LF to prevent salinity buildup in the root zone when irrigating with saline water and decrease it when irrigating with fresh water. Figure 8 illustrates the status of leaching fraction in the studied fields. The figure shows that only 2 cases out of 18 fields apply LF values between 10-15 percent, while most cases apply LF between 20- 40 percent. One third of the cases apply LF values of equal or higher than 50 percent, which means considerable loss of irrigation water for pistachio production.

4.2. Infiltration problem

High levels of sodium are common in the irrigation water sources used in pistachio orchards, but at the same time, irrigation water salinity is high, which is expected to do lead to infiltration problems in soil due to dispersion of soil colloids. This sort of interpretation could be followed by illustrating the relationship between salinity - SAR and salinity – CROSS index for 135 irrigation water sources (Figure 9). Based on these figures, it could be concluded that the flocculation charge surpluses the dispersion charge and its net effect is limited to no reduction in infiltration rate.

Adjusting SAR using equations 5 and 6 also reduced the predicted SAR_{adj} compared to the original levels (Figure 10), which shows that taking into account the effects of CO_2 partial pressure and carbonates dissolution damps off the predicted hazard of sodium.

In our study here, all the soil samples were also located in the no infiltration rate reduction part. Farmers, on the other hand, used to apply gypsum and other amendment chemicals with the wrong idea of saline soil reclamation. We reviewed 3 research papers regarding the responses of soils to different reclamation practices. Figure 11 shows the relation of EC-SAR in these research papers.

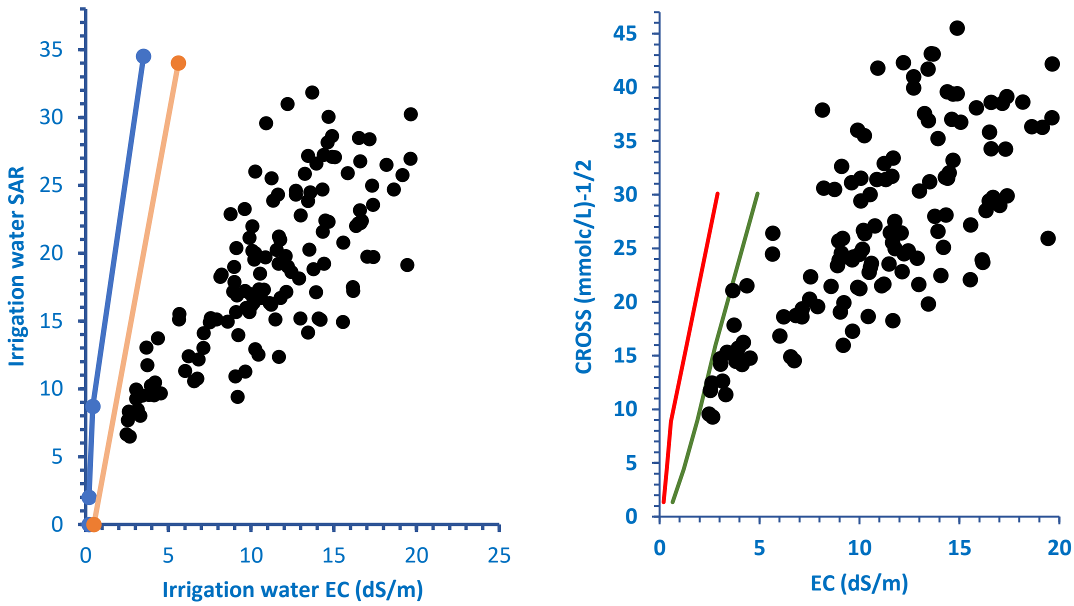

Figure 9. Interpretation of infiltration problem based on SAR and CROSS indices for 135 irrigation water samples. All samples located in the area of limited to no reduction in soil infiltration rate

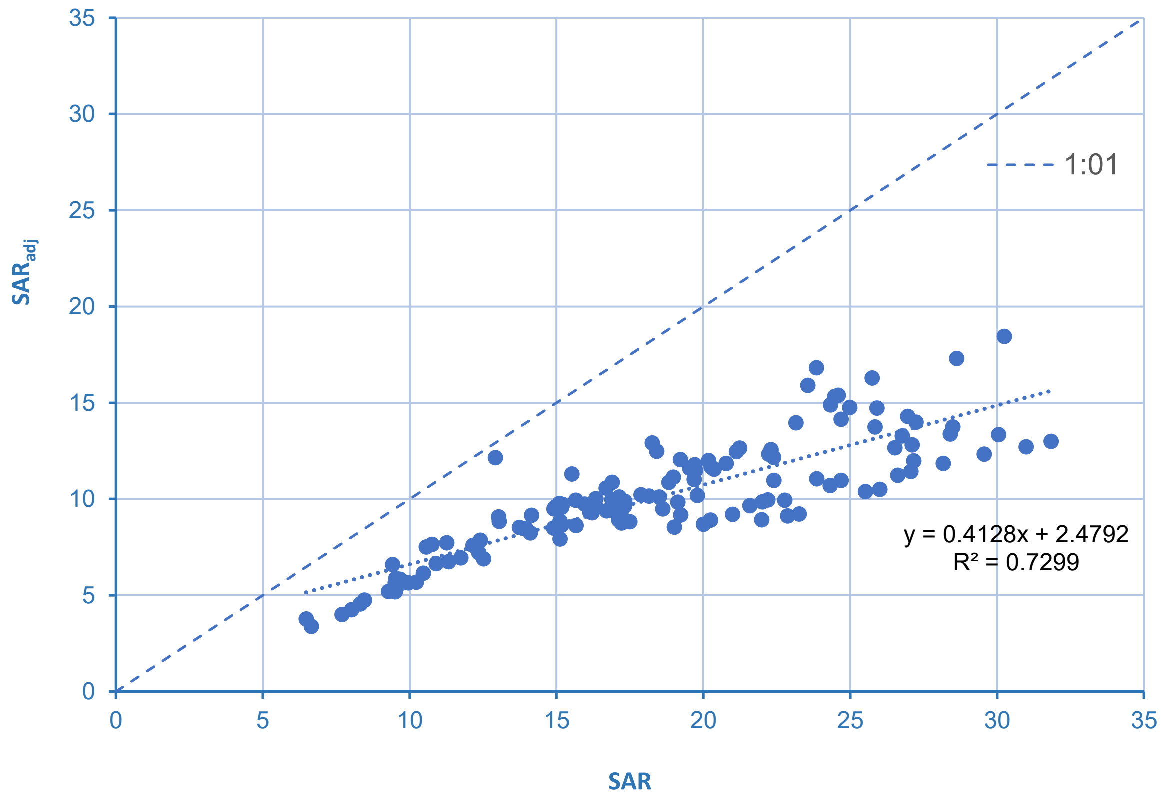

Figure 10. Calculated SAR_{adj} compared to SAR in 135 water samples

In a field research Rasouli et al., (2013) evaluated the effects of different levels of gypsum application on reclamation of a sodic soil in Fars Province, Iran (Rasouli, Pouya et al. 2013). The field was irrigating with a

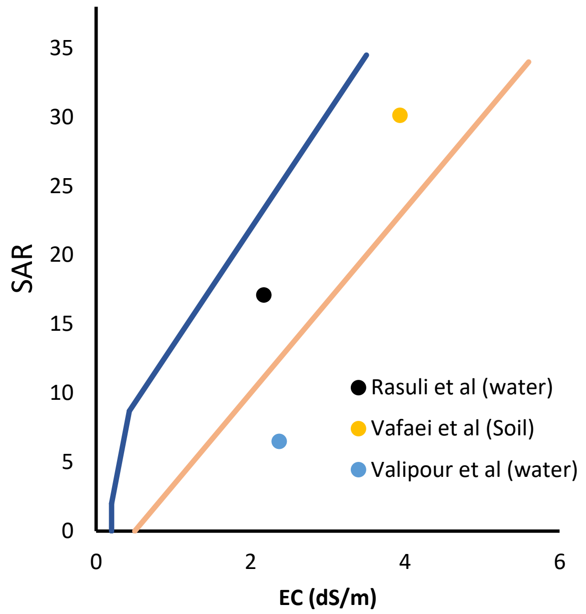

Figure 11. Review on the effect of gypsum on soil reclamation based on the literatures.

non-saline but sodic water in the downstream of Doroodzan River watershed. The authors have visited this field during the research when the untreated soil was completely dispersed and the effects of gypsum application on the field and soil were obvious from the start. Based on the figure 11, the risk of irrigation with this type of water is medium, while the field symptoms of dispersion were high. This type of irrigation water composition is rare, but is expected to spread in the lowlands and areas irrigated with drain water and/or wastewater. In another research the effects of gypsum and organic matter on reclamation of a sodic soil in southern Khuzestan is evaluated (Vafaee, Golchin et al. 2019). Although the chemical composition of irrigation water is not indicated, but the soil is located in the medium risk part. Applying 100% of gypsum requirement without organic matter showed the highest efficiency in chemical reclamation of soil. While in research on an extremely saline soil (ECe of 70-99 dS/m at different depths) and using a water which is located in no risk part of the graph, the application of gypsum showed no effect on leaching of salts from the root zone (Valipour and Sakhaei Rad 2011). This review reveals that, the reclamation treatments are effective when the soil and/or water composition is located in the area of medium or high risk.

4.3. Magnesium problem

Despite the reports on the widespread distribution of magnesium affected soil and water resources in some parts of Iran (Dehghani, Malakouti et al. 2012, Qadir, Sposito et al. 2021), the reports on its negative effect or interaction on yield or soil quality attributes is very limited (Dehghani, Rahnemaie et al. 2021). The risk of irrigation with high magnesium water sources seems to be reduced in soils. Figure 12 shows the Mg/Ca ratios of irrigation water sources in comparison with that of respective soils. In almost all cases, the Mg/Ca ratio in the soil is lower than that of irrigation water, except for the fields number 4 and 6. Field number 9 was irrigating with a high magnesium affected water (Mg/Ca of higher than 3), while the ratio in the soil was reduced to lower than unity. The problem may be related to the application of gypsum in the fields (Schubert and Qadir, 2024) or the dissolution of indigenous soil carbonates.

The Mg:Ca ratios in soil are typically lower than those in the irrigation water due to several interacting chemical processes. One key factor is the application of gypsum, which adds soluble calcium without affecting magnesium levels, thereby reducing the Mg:Ca ratio in the soil solution. Additionally, the dissolution of native calcium carbonate ($CaCO_3$) in calcareous soils contributes extra calcium to the soil solution, further lowering the Mg:Ca ratio compared to irrigation water. In contrast, magnesium-bearing minerals are often less soluble and less abundant in these soils, leading to relatively lower magnesium concentrations.

Moreover, calcium and magnesium ions in soil undergo distinct precipitation and dissolution behaviors that depend on factors such as the ion concentrations in solution, partial pressure of CO_2, clay mineralogy, and the presence of $CaCO_3$ phases in the soil (Suarez and Rhoades, 1982). These complex geochemical interactions—particularly important in calcareous environments—are not explicitly evaluated in this study but play a significant role in shaping the observed differences in Mg:Ca ratios.

4.4. Alkalinity problem

Regarding the pH, all cases studied in this research and almost all pistachio cultivated areas in the country have pH values of higher than 7, but these cases do not suffer from alkalinity problems as the RSC in all cases is positive and the pH values of higher than 8.2 are seldom. However, there are considerable cases to suffer from high bicarbonate concentration in irrigation water or soil solution, as it may limit the availability of micronutrients for plant (Karimi, Tavallali et al. 2020). Figure 13 shows the probability distribution curve for the bicarbonate concentration in the 135 studied water samples.

Almost 40 percent of these water sources have bicarbonate content of higher than 5 meq/L which is considered as a critical value to reduce leaf chlorophyll intensity (Shahabi, Malakouti et al. 2005). These fields seem to be prone to micronutrients deficiency and the nutrients have to be applied as chelates to protect them in the calcareous environment of soil.

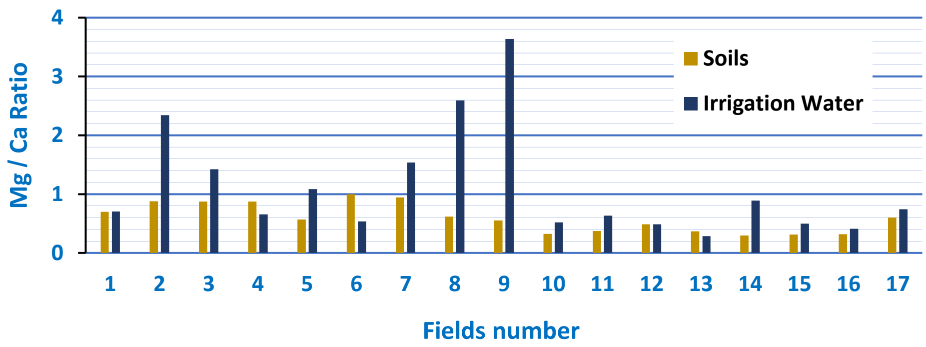

Figure 12. Comparison of Mg/Ca ratio in irrigation water and respective soils

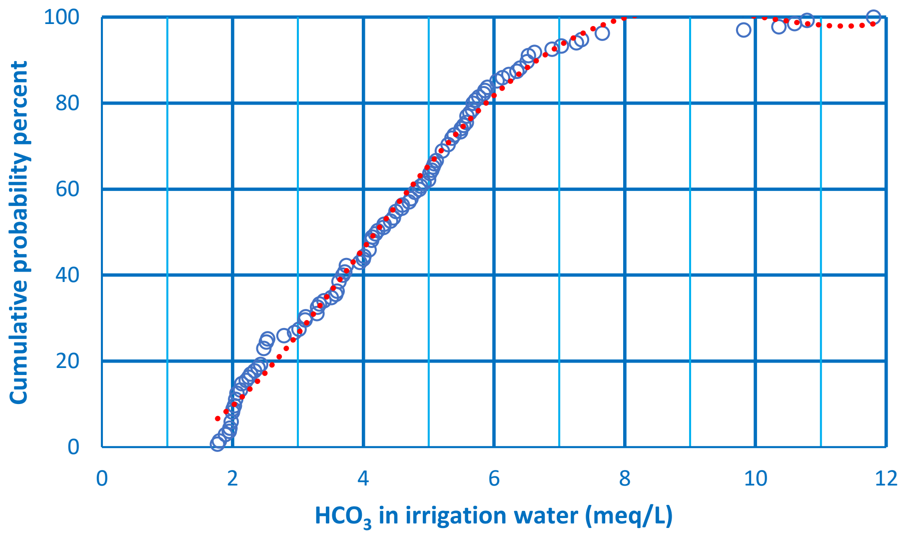

Figure 13. Cumulative probability distribution curve of bicarbonate content in 135 studied water samples

4.5. Management strategies for assessment and management of soil salinity in the field

To manage salinity in the field, it is necessary to continuously assess the soil salinity status and the leaching fraction during different irrigation events. For this purpose, installing a simple device called a “wetting front detector” can enable continuous monitoring of these factors (Hasheminejad, 2011). The Wetting Front Detector (WFD), which is specifically designed for this purpose (Stirzaker and Hutchinson, 2005), is capable of sampling soil solution that freely drains during the early stages after irrigation. When installed at different soil depths, this device can indicate whether water has reached various depths, effectively allowing estimation of the wetting front’s infiltration depth. Additionally, by measuring the salinity of the collected soil solution, the adequacy or inadequacy of leaching in controlling root zone salinity can also be assessed.

Hasheminejhad (2011) used this device in pistachio orchards in northern Ardakan to estimate the leaching fraction, and subsequently applied it in steady-state models to estimate soil salinity. The results showed that this tool can be used to estimate both the leaching fraction and soil salinity. In pistachio orchards, accurately determining the depth of active root development for water uptake is challenging. Therefore, in steady-state soil salinity models that rely on the water uptake pattern by roots, using the wetting front detector to estimate soil salinity requires knowledge of the active root depth. Rahimian et al., (2018) used a combination of the wetting front detector and an electromagnetic induction device to estimate soil salinity. Through a trial-and-error approach, they were able to estimate the active root depth in pistachio trees, which corresponded well with actual evapotranspiration data from that depth.

Biological amendments (Mazloom et al., 2013) and chemical amendments (Rasouli and Kiani Pouya, 2011) are effective for reclaiming sodic or saline-sodic soils, whereas for saline soils, leaching remains the only available management strategy. Although phytoremediation is not effective in reducing soil salinity under irrigated conditions, it is quite effective in mitigating sodium hazards. Sodic and saline-sodic soils require a soluble source of calcium to replace excess sodium on soil exchange sites. Using chemical amendments can be costly and sometimes inaccessible for certain farmers. Research conducted over recent decades has shown that salt-tolerant and moderately salt-tolerant plant species such as Kallar grass *(Leptochloa fusca L. Kunth)*, sesbania *(Sesbania aculeata)*, and alfalfa (*Medicago sativa*) can contribute to the reduction of salinity and sodicity in these soils (Qadir et al., 1996). These plants enhance the partial pressure of carbon dioxide in the root zone and acidify the soil solution, thereby facilitating the dissolution of calcite minerals (Qadir et al., 2007).

In a pot experiment, Mazloom et al. (2013) tested chemical treatments (including the application of gypsum and sulfuric acid) alongside biological methods (including the cultivation of sesbania, *Poa annua*, and *Rubia tinctorum*) to remediate a sodic soil. Their results indicated that planting *Rubia tinctorum* had a significantly greater impact on improving the physical and chemical properties of sodic soil compared to chemical treatments.

To estimate the leaching requirement of crops, various formulas (Hoffman and van Genuchten, 1983), graphs (Hasheminejad and Besharat, 2017), and models (Corwin et al., 2007) can be used.

Other field-level salinity management strategies include the use of mulches to reduce capillary rise and evaporation, enhancing drainage efficiency, reducing salt accumulation in the soil by minimizing irrigation with saline water, and planting salt-tolerant or halophytic species.

4. Conclusion

A. Management priorities

- **Root zone salinity control:** High salinity in irrigation water and subsequent salt accumulation in the root zone remain the key threats to sustainable pistachio production in the region. While farmers have partially mitigated soil salinity through leaching, excessive leaching fractions (>30%) lead to significant water losses through deep percolation (Hasheminejhad, 2011).
- **Water use efficiency:** Improved irrigation management—especially optimized leaching fractions and better drainage design—can reduce water waste while maintaining salinity control.
- **Appropriate use of amendments:** Since sodicity was not a major issue in this study, applying amendments like gypsum—typically used to reclaim sodic soils—may not reduce salinity or enhance leaching efficiency, and could represent unnecessary cost and effort.

B. Emerging risks

- **Magnesium hazard:** Elevated Mg concentrations and increasing Mg/Ca ratios are being observed in irrigation water and soils. Because magnesium is less effective than calcium at promoting flocculation of soil particles, high Mg/Ca ratios may contribute to long-term soil structural decline.
- **Bicarbonate accumulation:** High bicarbonate levels can lead to calcium precipitation, reducing Ca availability and further increasing the Mg/Ca ratio in soil solution—raising the risk of sodicity and infiltration problems over time.
- These issues require site-specific management strategies, including water source blending, use of acidifying amendments, or irrigation guidelines based on cross-indices such as CROSS or adjusted SAR formulas.

C. Research gaps

- **Advanced modeling needs:** Future research should focus on developing or validating dynamic models that incorporate calcium and magnesium precipitation/dissolution reactions, particularly in calcareous soils.
- **Field-based evidence:** On-farm experiments comparing irrigation and amendment strategies under varied leaching regimes can provide more practical, region-specific recommendations.
- **Monitoring and assessment:** Regular monitoring of Mg/Ca ratios and bicarbonate concentrations should become a standard component of salinity and sodicity risk assessment in irrigated orchards.

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