ISSN No: -2456-2165 https://doi.org/10.38124/ijisrt/25sep1363

Review on Reclamation of Saline Soil by Leaching

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Publication Date: 2025/11/06

Abstract: Soil salinity is a significant and pressing environmental issue, particularly in arid and semi-arid climates. These climates depend on highly saline water for irrigation, and their rainfall is very little and insufficient to leach salts from the plant's root zone (surface layer of soil).

Therefore, researchers have resorted to many methods to manage saline soils (salt extraction, addition of amendments, cultivation of halophytic plants, removal of salts from the soil surface, etc.). However, not all reclamation techniques are suitable for all types of soils affected by salinity. One of the most important and widely used methods is salt leaching (Adding water to dissolve salts and transport them through water movement down the soil and away from the root zone). However, if added in excessive quantities, this method consumes water, removes nutrients from the soil, and raises the groundwater level. Researchers developed differential mathematical equations to calculate the quantity of water that must be applied to leach the salinity from the soil while minimising water usage to avoid leaching away the plant's nutrients and preventing the rise of the groundwater. However, the reclamation strategy must be designed based on the site's detailed requirements, including the type of soil, quantity and quality of salts, groundwater level, water availability, plant species, and climate, taking into account the relationships between these factors. These equations did not account for all the previous parameters and were limited to the specific conditions of the study sites.

Simulation programs are essential for creating equations or methods that can be widely applied, as it is difficult to provide all the necessary conditions (parameters) in specific locations. Therefore, this study reviewed all the factors affecting extraction that researchers studied in previous studies, in addition to the most common, applied, and reliable simulation methods in this field. Thus, simulation can be done by applying these parameters.

Keywords: *Reclamation of Saline Soils, Leaching Equations, Numerical Modelling and Simulation (HYDRUS, Artificial Intelligence).*

How to Cite: Husam Hasan Abdulaali; Christopher Teh Boon Sung; Afrah Mahdi Saleh Al-Obaidi; Muhammad Malik Yassin (2025). Review on Reclamation of Saline Soil by Leaching. *International Journal of Innovative Science and Research Technology*,10(9), 3167-3181. https://doi.org/10.38124/ijisrt/25sep1363

I. INTRODUCTION

➢ *Overview of Soil Salinity*

Soil salinity is widely recognised as a critical environmental challenge affecting approximately 1.4 billion hectares of agricultural area globally, accounting for over 10% of the Earth's total land area (Atta et al., 2023). The process of salinisation is driven by both natural methodologies, such as the weathering of minerals and the gradual withdrawal of oceans, and anthropogenic activities, including improper irrigation practices, land clearing, mining, and oil extraction (Aslam & Prathapar, 2006; Debez et al., 2010; Hassani et al., 2021). Salinity is categorised into two types: primary salinity, which inherently occurs, and secondary salinity, which is predominantly a development of human activities. The latter is particularly pronounced in regions with low and moderate rainfall, where salts accumulate in the soil profile due to insufficient rainfall (Jamil et al., 2011).

Many factors such as soil texture (sandy, silty, and clay soils), climatic changes, the depth of groundwater, agricultural practices can be influenced on soil salinity (Hassani et al., 2021). Salinity, especially in the arid region, is resulted from highly elevated of soil salts concentration on the soil surface which leads to increasing the salts into the soil. Rising temperature and irregular rainfall which linked to climatic changes are intensified the salinity. (Hassani et al., 2021; Jamil et al., 2011). Furthermore, drainage, leaching processes are highly affected by soil structure, whereas the poor soil structure leads to inhibit the processes (Caon, 2019).

The environmental sustainability, food security, and soil productivity are significantly endangered by salinity.

The amount of rain in the semi-arid region is significantly insufficient to irrigate the agricultural lands. Precipitation cannot leach salt from the soil; additionally, in some areas, saline water has been used to irrigate agricultural fields. Many mathematical models have been used to determine the amount required to leach the salts into the soil. These models have limitations in calculating all factors that are influenced by soil type, groundwater level, and environmental conditions. Furthermore, adding more water rules out the leaching of necessary nutrient elements from the soil. For these reasons, it is necessary to develop mathematical models to calculate water depth leaching by using simulation approaches. These models can encompass all the factors affecting soil salinity reclamation. This study provides a comprehensive review of various models and suggests some effective models, such as HYDRUS and AI, for assessing soil salinity-enhancing strategies.

➢ *Impact of Salinity on Soil:*

Soil salinity and sodium content play important role to threat the agricultural systems (The soil's physical, chemical, and biological traits), thus threatening plant growth and soil health (Kramer & Mau, 2023). High salt concentrations harm the soil's physical and chemical properties, leading to soil structure degradation, reduced fertility, and impaired crop productivity. Category of salt-affected soils into several categories based on their electrical conductivity (EC), exchangeable sodium ratio (ESP), and pH levels: saline soils (ECe > four dS m^{-1}, pH < 8.5, ESP < 15), saline-sodic soils (ECe > 4.0 dS m^{-1}, pH < 8.5, ESP > 15), and sodic soils (ECe < 4 dS m^{-1}, pH > 8.5, ESP > 15) (Richards, 1954). Increased salinity results in a higher concentration of dissolved salts in the solution of soil. Alternatively, sodicity is characterised by an imbalance of sodium (Na^+) in the soil. It is also expressed by the absorption of sodium ratio (SAR) or the ratio of sodium exchangeable (ESP) (Stavi et al., 2021; Westhoff et al., 2024). The value of ESP in sodic-soils have 15 or more which means SAR is approximately 13. (Stavi et al., 2021). The sodium ion in sodic soils displaces necessary such as magnesium and calcium ions which mean increasing soil structure disruption. Soil structure disruption leads to reducing soil permeability, water infiltration, and penetration of roots. (Fay & Shi, 2012; Al-Fadhli et al., 2007). Furthermore, plant germination can be influenced by increasing evaporation and salts curst formation on the surface. (Keiffer et al., 2002).

The soil, which has poor water infiltration, low air penetration, and deteriorated soil structure, is called sodified. High Na^+ contents can negatively affect plant nutrition (Westhoff et al., 2024). Sodic soils typically hold a pH above 8.5, creating an alkaline environment that is toxic to plants due to bicarbonate (HCO_3^-) produced by water evaporation or the biological reduction of $SO4^{-2}$. Salts such as gypsum, magnesite, sodium carbonates, sodium sulphates, magnesium sulphates, potassium chloride, and sodium chloride can readily be released in arid and semi-arid states, increasing the proportion of Na+ ions and leading to soil sodification. Na-bearing minerals in parent gravel also contribute to sodification and salinisation (Stavi et al., 2021).

➢ *Impact of Salinity on Plants:*

Salinity has an effective influence on plant stress, growth, productivity, and overall development. Salinity sensitivity levels vary among the crops. The carrots and strawberries are highly sensitive to salt, whereas some crops exhibit great tolerance for salinity, such as barley and date palms. Although there are salt-tolerant species, growth is severely limited due to osmotic tension, which reduces water uptake (Ullah et al., 2021; Chele et al., 2021).

Salinity imposes osmotic tension by decreasing moisture availability in the root zone, stunting plant growth and potentially decreasing crop yields by up to 70% in extreme cases (Warrence et al., 2002). Sensitive crops, such as rice and beans, are more at risk. High sodium chloride levels also affect the absorption of other nutrients, leading to deficiencies in essential elements such as potassium and calcium, which, in turn, impair photosynthesis, protein synthesis, and other metabolic processes. Excessive salinity not only reduces the turgor pressure exerted by plant roots on the soil but, in severe cases, can also impair a range of metabolic processes, including photosynthesis and nutrient absorption. Plant hindering growth, lack of cytotoxicity and sodium chloride is highly affected by sodium chloride. These factors can advese influence a plant's capable to regulate growth and remarkably lower its tolerance to various external stresses (Dos Santos et al., 2022).

The two potential solutions are utilized to mitigate salinity impacts either cultivate salt-tolerant crops such as barley or practicing specialize management to reach to productivity improvement (Machado & Serralheiro, 2017). Photosynthesis is impacted by salinity by reducing leaf size and chlorophyll content (Shrivastava & Kumar, 2015). Furthermore, increasing accumulation salts in the soil can result the reactive oxygen species (ROS). The ROS has some adverse impacts on the plant, such as: essential components reaction with plant cell, oxidation, which is of three types - the vital plant parts oxidation, lipid oxidation, and protein oxidation- DNA damage, enzyme disruption, and hormonal imbalance (Atta et al., 2023).

Mitigating the impact of saline soils is critical for managing salt-influenced soils and recycling agriculture and the environment. The effective strategies can such as applying irrigation techniques, removing salts by a proper drainage system, improving soil health by crop rotation, cultivation some salt-tolerant species, and applying organic matter or other soil conditions to improve soil structure and low SAR level in the soil. Decreasing soil degradation can be maintained the balance between water and salts in the soil. This review aims to emphasise applying significantly suitable reclamation approaches to agricultural productivity maintenance and mitigate desertification by determining leaching fractions in an accurate way under a variety of environmental conditions.

ISSN No: -2456-2165 https://doi.org/10.38124/ijisrt/25sep1363

II. RECLAMATION OF SALINE SOILS

Several methods have widely applied to reduce the salt-affected soils, including extraction of salt, adding amendments, reforestation with halophytes, and leaching the salt from the soil (Shaygan & Baumgartl, 2020). These approaches, however, cannot always be implemented individually; they are most effective as part of a comprehensive reclamation programme that incorporates extraction to facilitate the dissolution of soluble salts (Owen et al., 2019; Shaygan & Baumgartl, 2020). Dissolved and soluble salts can transport downward with water movement in the soil, resulting from the extraction process. Using the adopting method is adding more amount of irrigation water to soil surface to salinity management in the root zone (Al-Tamimi et al., 2023). Leaching and reclamation salts from the saline soils are considered saving time, easy to apply, and economical approach. (Ghafoor et al., 2004; Hoshan, 2022).

The process which describes entering water into the soil from the surface depending on the time is called infiltration rate. The infiltration ratio represents the ration of water which absorbed by roots and water infiltrates water for below depths. (Rhoades, 1974; Rhoades & Merrill, 1976; Ayers & Westcot, 1994; Costa et al., 2015).

It reflects the controlled release of water and dissolved minerals from the substrate of potted plants with specific irrigation amounts. The proportion of extracted water volume from the container to the water which is used by irrigation is called the infiltration ratio (Owen et al., 2019). Leaching fraction (LF) strategy considers an effective strategy and can increase the resulting favorable reclamation outcomes. (Ndiaye et al., 2022). This renders leaching salts a viable option for reclaiming saline soils and enhancing crop production (Dudley et al., 2008). Findings indicated that applying a 0.20 extraction ratio of saline water resulted in a 6.6% decrease in soil pH, a 46.1% reduction in electrical conductivity (EC), and a 46.4% decline in the sodium adsorption ratio (SAR) (Hamza et al., 2021). An experiment by Gürgülü & Ul (2024) in Turkey, involving the cultivation of pepper (Capsicum annum L.), one of the most significant vegetables grown under greenhouse conditions, examined extraction ratios of 15–20% (LF1) and 35–40% (LF2). The results revealed that while the extraction fractions did not significantly impact yield, they maintained overall productivity. Similarly, in nursery applications, irrigation based on a target LF of 0.15 to 0.20 or monitoring substrate moisture has shown potential in mitigating nutrient loss through extraction, thereby prolonging the efficacy of controlled-release fertilisers (Kochba et al., 1990; Stanley, 2013; Chappell et al., 2013). Routine testing of extraction fractions and adjusting irrigation to maintain the target LF resulted in a 43% reduction in water usage in a Virginia nursery (Stanley, 2013). The leaching or extraction process can effectively alleviate soil salinity by flushing out excess salts, thereby improving soil conditions for plant growth. Implementing extraction fractions of 10% and 20% in saline irrigation helps sustain lower salt concentrations in the root zone, enhancing crop yield and biomass. This technique is vital for managing soil salinity and bolstering agricultural productivity in salt-affected areas (Manzoor et al., 2019). Reduced water usage has resulted in lower costs for chlorine, electricity, fertiliser, and herbicides. Other benefits of reduced irrigation volumes include improved crop uniformity and a decrease in disease issues (Million & Yeager, 2019; Million & Yeager, 2020). Owen et al. (2008) found that targeting an LF of 0.10 to 0.20 decreased leaching volume by 64% and lowered dissolved phosphorus concentration by 64% without adversely affecting the dry weight of the plant. Tyler et al. (1996) noted that a low LF of 0 to 0.20 curtailed nitrate and phosphorus abundance compared to an LF of 0.40 to 0.60.

Water irrigation through the soil, however, cannot dissolve toxic ions (e.g., Na+ and Cl^-), whereas important essential elements can be particularly leached under conditions of plant stress (Lacerda et al., 2016; Lacerda et al., 2018). Notably, the salinity of groundwater is increased by this process. For a long-term risk, the groundwater quality is susceptible to contamination (Al-Tamimi et al., 2023). The chemicals in the soil can be dissolved by the infiltrated rainwater and transported into the soil profile. Moreover, groundwater infiltration into the soil is likely to increase crop yields (Costa et al., 2015).

Due to uncertainties in soil salinity control and management, along with the various statistical models used to estimate the leaching ratio, there is considerable variation in the recommended water amount for soil reclamation. Although numerous examinations have been published utilising mathematical models to simulate the reclamation of saline soils, the volume of leaching water required to reclaim these soils is generally computed using empirical formulas (Rhoades & Loveday, 1990; Shankar & Evelyn, 2019), and many of these do not consider all influencing factors (including soil and environmental factors) collectively. Recently, several studies have utilised modern technologies to modify the infiltration fraction of applied irrigation water in saline soils. The evapotranspiration rate (ETc), particularly under environmental conditions such as sunlight duration, temperature, and humidity, has been recently estimated by a machine learning (ML) technique. The LF is modified by the reasonable ETc, which further enhances the effectiveness of the primary wash cycle in conserving moisture compared to traditional methods. By using ML techniques, the model has been extensively validated for measuring the success of reference evapotranspiration (ETo) (Bashir et al., 2023). Thus, effective water management is essential, incorporating the water needed to extract salts from the root zone while avoiding the removal of minerals crucial for plant growth due to excessive applications.

III. GENERAL CONCEPT OF LEACHING FRACTION (LF)

Leaching Fraction (LF) is defined as the amount of liquid infiltrated divided by the amount of irrigation water applied to the container (Krofft et al., 2020; Million & Yeager, 2019):

ISSN No: -2456-2165 https://doi.org/10.38124/ijisrt/25sep1363

$$Leaching\ fraction = (leachate\ recovered)/\ (total\ applied\ irrigation)$$

This method focuses on flushing salt from the surface soil layer (45-60 cm) into the subsurface layers beneath the root zone (Kerin, 1990; Kader et al., 2000). The success of this method hinges on the use of high-quality water, which must have a low concentration of electrolytes. This water seeps through the soil, facilitating the dissolution and downward movement of salts and preventing excess salt accumulation in the root zone. The amount of water required for soil reclamation is determined by several factors, including its texture, the amount of salts present, the volume of the soil to be reclaimed, the required salt level in the root zone, and the plants to be planted after reclamation (Kader et al., 2000; Biswas & Biswas, 2014).

IV. LEACHING FRACTION MEASUREMENT METHODS

The leaching fraction is considered an indicator of the water volume used via irrigation, the planned target, substrate saturation, and adequate leaching of salts. Technically, the leaching fraction is the volume of water leached from the base of a container, separated by the volume of water used to fill that container $(leaching\ fraction = water\ leached \div water\ used)$ (Figure 1) (Owen et al., 2019).

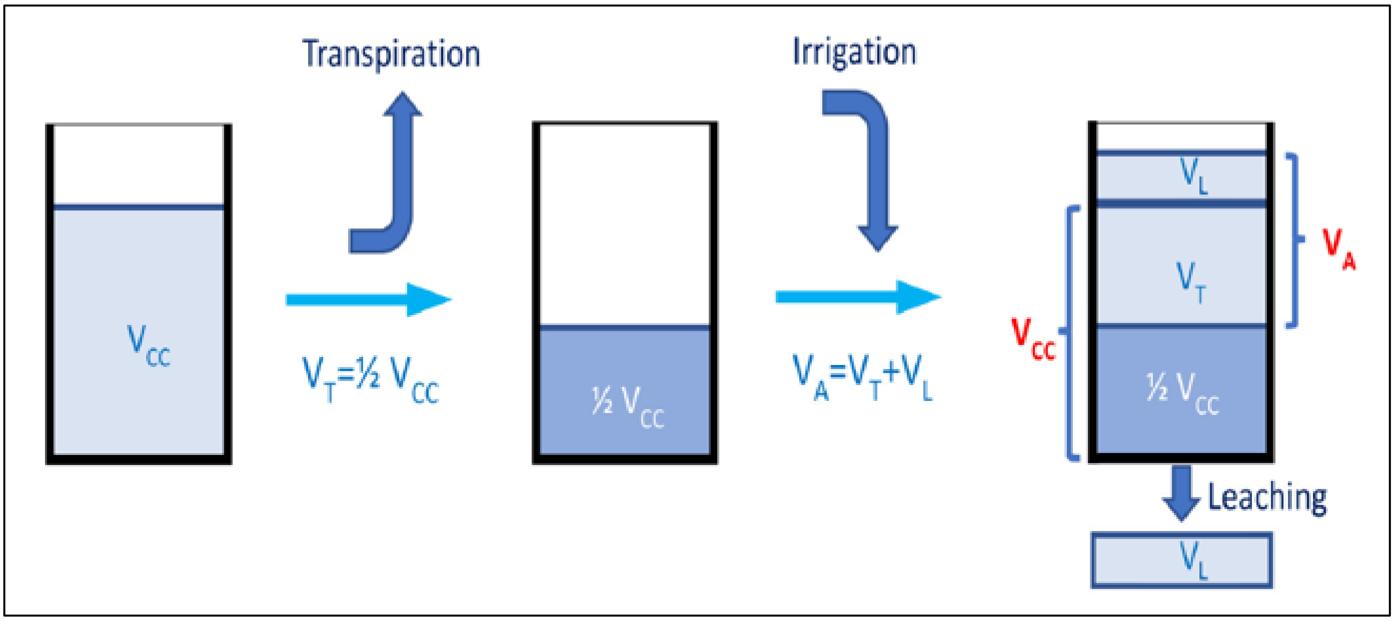

Fig 1 Leaching Fraction Measurement Methods

Table 1 Leaching Fraction Measurement Methods

1. The container has just been irrigated, and the substrate is at container capacity (V_{CC}).	2. Water is lost through transpiration (V_T), and for this example, is ½ of Vcc.	3. The water remaining in the container is ½ of V_{CC}.	4. Irrigation applies water (V_A) to replace transpiration losses (V_T) and the volume to be leached (V_L).	5. Since irrigation (V_A) applied more water than the substrate can hold (V_{CC}), excess water leaches (V_L) from the container, bringing salts.

Figure 1 illustrates that after irrigation, the substrate retains the maximum water content (Vcc). Irrigation replenishes the water lost from the substrate through evapotranspiration (ET). Additionally, a certain amount of water (VL) must be applied to leach out the salts dissolved in the substrate water from the container, following the modification made by Evans (2017) as cited by L. Oki (Owen et al., 2019).

- *Volume Based Measure of Leaching Fraction*

To determine the amount of water used during irrigation, place an open container the size of the plant's pot next to the plants to collect the irrigation water. Place another container lined with plastic or a tightly sealed bucket under the plant to collect the water that seeps through the substrate, ensuring that water does not run down the sides (see Figures 2 and 3). One hour after the end of the irrigation cycle (including all cycles if using recurring irrigation), measure the amount of water that has seeped from both the planted and empty pots.

The combined amounts allow calculation of the leaching percentage (LF), defined as the volume of seepage divided by the volume of water used. For example, if 1 litre of water is added to an empty pot and 0.25 litres seep from the pot with the plant, the LF is 0.25, or 25%. This method indicates the amount of water that has seeped through the substrate, helping to optimise irrigation by ensuring adequate salt leaching and substrate saturation.

ISSN No: -2456-2165 https://doi.org/10.38124/ijisrt/25sep1363

Measuring multiple plants in different areas improves accuracy and can reveal whether the system is running consistently or inefficiently. Measurements should be taken approximately one hour after irrigation is complete on dry, sunny days to reflect actual water usage. The filtration fraction is also used to adjust the irrigation schedule by comparing measured values to target LF ranges (typically 15-30%), and adjusting irrigation duration and volume accordingly (Owen et al., 2019).

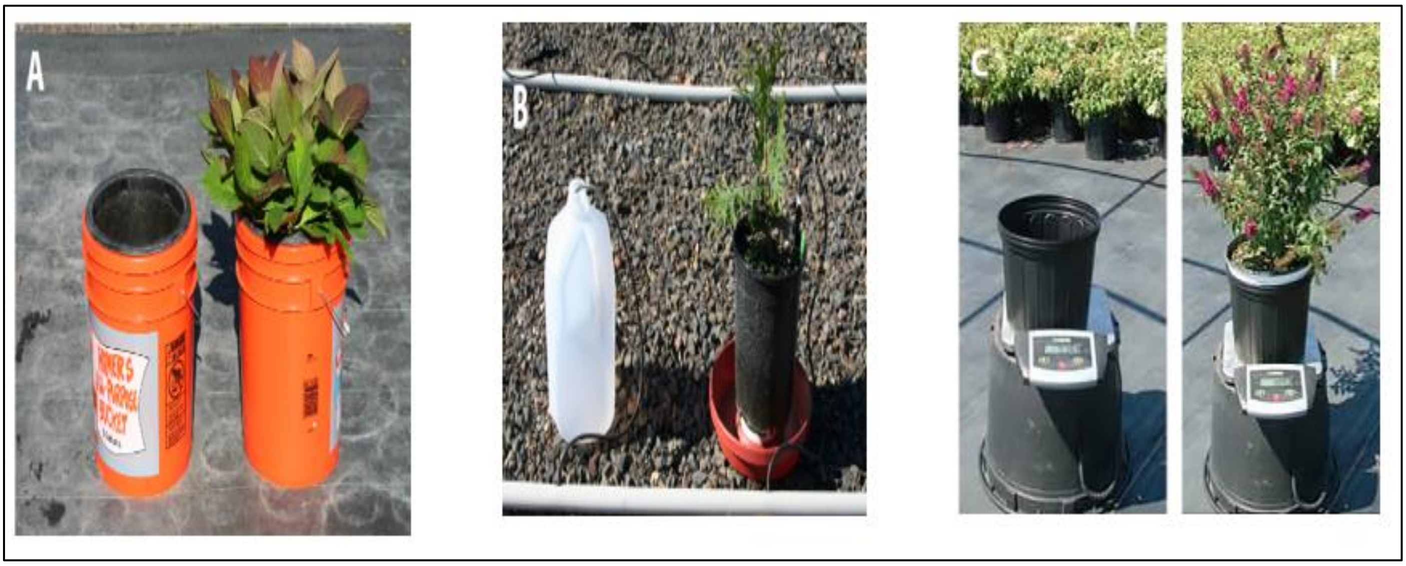

Fig 2 Volume Based Measure of Leaching Fraction

Figure 2 illustrates several setups used to measure leaching based on volume. (A) shows an empty, unplanted container on the left and a planted container on the right, both placed inside 5-gallon buckets with perforated lids to collect the leaching. (B) illustrates a microirrigation setup in which a sprinkler stake has been placed inside a 1-gallon milk jug, and the planted container is connected via tubing to a plant saucer on the right to collect the leachate. (C) depicts a solid container with no drainage holes to collect leachate (left), along with a planted container embedded within it (right). (Photos by Jim Owen for corners A and B, and Gene Stanley for corner C) (Owen et al., 2019).

➢ *Determining the Infiltration Rate by Volume Method:*

- Place the plants securely inside containers placed in similarly sized buckets to ensure that all the water added to the plant drains through the substrate and seeps out from the base of the container. If leak-proof buckets are not available, the container can be lined with a plastic bag of the same diameter.
- Next to each container, as in step 1, place a bucket or container lined with a plastic bag of the same size to collect the added water. If using micro-irrigation, place the emitter inside a milk jug or clean bottle (Figure 2a).
- Perform a normal watering cycle.
- One hour after watering has stopped, collect and measure the amount of water that has seeped from the containers containing the plants.
- Measure the amount of water collected in the empty containers.
- Calculate the infiltration rate for each plant by dividing the amount of water that has seeped (from step 4) by the amount of water that has been added (from step 5).

$$\text{Leaching fractio} = \frac{\text{planted container leachate (leached)}}{\text{empty container with water (applied)}}$$

➢ *Weight-Based Dimensions of Leaching Fraction*

The grower can determine a leachate ratio less than or equal to 1.0 by calculating the capture factor using an industrial scale or a washing scale. In the metric system, 1 mL of water equals 1 gram. Therefore, when a plant is weighed in grams, rinsed, and reweighed, the difference in grams represents the volume of water used in millilitres. Before rinsing, the empty bucket or container (as in Figure 2c), designed without drainage holes to collect the leachate, is weighed along with the planting container. They are placed tightly together to ensure that only the water that has seeped into the bucket enters the bucket through the substrate. To prevent the soil from absorbing the leachate during the one-hour drainage period after watering, a spacer can be placed between the plant container and the leachate collection container. Irrigation begins, and an hour is then allowed after the watering process is completed. The net is then removed from the containers, and the bucket containing the leachate is weighed, subtracting the weight of the bucket before watering to determine the weight of the leachate only. The planted container is then weighed, and its pre-irrigation weight is subtracted to calculate the weight of water retained within the plant. The weight of the leached water is added to the weight of the retained water to determine the total weight of the applied irrigation water. The infiltration rate is then calculated by dividing the leached weight by the total weight of the irrigation water (Owen et al., 2019).

Fig 3 Weight-Based Dimensions of Leaching Fraction

Figure 3. Images show (a) the saucer, (b) the plastic bag, (c) the plugged bucket, and (d) the plastic skirt methods used in nurseries to accurately collect water and leaching from small and large containers when applying the size-based leaching fraction method (Owen et al., 2019).

- *Determining Leaching Fraction Utilising the Weight-Based Method*

- ✓ Weigh an empty bucket to collect the leachate.
- ✓ Weigh the pot.
- ✓ Place the pot inside the empty bucket.
- ✓ Add irrigation water for a regular watering cycle.
- ✓ After an hour of stopping watering, remove the pots.
- ✓ Weigh the bucket with the leachate, and subtract the pre-watering weight in Step 1 to obtain the leachate weight.
- ✓ Weigh the pot, and subtract the pre-watering weight (Step 2) to obtain the weight of water retained in the pot.
- ✓ Add the weight of the leachate (Step 6) to the amount retained in the pot (Step 7) to determine the total amount of irrigation water used.
- ✓ To get the leaching fraction, divide the weight of the leachate (Step 6) by the total amount of irrigation water used (Step 8).

$$\text{Leaching fraction} = \frac{\text{weight of leachate (leached)}}{\text{weight of water applied (applied)}}$$

V. FACTORS CONTROLLING THE PROCESS OF LEACHING SALTS FROM THE SOIL

Several factors have affected the efficiency and effectiveness of leaching salts from the soil. We review the most important of them, which have never been mentioned in most researchers' equations for calculating the amount of water applied in the reclamation process:

- ➢ *Hydraulic Properties of the Soil.*

Soil hydraulic properties play a major role in controlling the leaching of salts from the soil. Here is how these properties play a role:

- *A-1- Soil Texture:*

Sandy soils have large pores (macropores), which allow water to drain into the soil quickly. Consequently, salts can be easily leached out of the surface layers. However, these soils may require large amounts of water because they cannot dissolve salts due to rapid water release. In contrast, clay soils have small pores (micropores), which slow down water infiltration into the soil. The clay soil's ability to leach salts is limited. The water often accumulates on the surface, causing the soil to become saturated, and the infiltration rate becomes less efficient. On the other hand, loamy soil is between sandy and clay soils in terms of hydraulic properties. It has medium permeability and better water retention capacity (Tunc & Sahin, 2015).

- *A-2- Soil Structure:*

Well-structured soils (aggregated soils) can more effectively infiltrate water because they contain channels and pores that allow water to move, increasing the efficiency of salt leaching (Siyal & Leeds-Harrison, 2001). In contrast, compacted soils have low porosity, which reduces water flow through the soil. This leads to the soil's inability to effectively leach salts, as the salts remain in the upper layers (Osman, 2018). If the soil contains large pores resulting from the activity of roots or microorganisms, water can move more quickly and deeper into the soil, facilitating the leaching of salts (Shokri et al., 2024). Large pores also contribute to improving drainage and leaching excess water. However, water is confined to the upper layers, lacking large pores, and therefore has difficulty moving down and accumulating salts in these layers. Soils that retain water for extended periods require more water for leaching. For example, the water capacity in clay soil is high which means that the soil can significantly retain the water before water drainage. The clay soil, therefore, which has salts, needs more water drain the salt away (Osman, 2018).

- *A-3- Soil Permeability:*

Water movement in sandy soil is fast because its permeability is very high, making it easy to leach salts away. Because of, however, their high permeability, the amount of water which is used to drain the salt away is high. Additionally, the low permeability of clay soils results in a

ISSN No: -2456-2165 https://doi.org/10.38124/ijisrt/25sep1363

high water-holding capacity, requiring a prolonged period and substantial quantities of water to achieve the salt-washing process. The careful drainage management requires to use to achieve the salt-washing process. Improving soil physical properties such as soil water infiltration ans well-strucutered soil increase salt washing efficiency. The most important characteristics to enhance salt-water efficiency is soil texture and soil structure (Osman, 2018).

➤ *Soil Salinity*

Soil salinity is a main element which influences and controls the salt-leaching process in different approaches. Soil water movement is significantly affected by high salinity which leads to leach the salt away. The soil salinity controls processes are:

- *B-1- Effect on soil structure*

The high concentration of sodium in soil can deteriorate the soil structure. The reason is that the sodium disperse soil particles and sodium ion can lead to reduce some soil physical properties such as soil permeability. The salt leaching in sodic soils is considered a challenge because of decreasing drainage water and increasing soil compaction (Gangwar et al., 2020; Oster et al., 1999).

- *B-2- Control the amount of water required*

The low-salinity soils required less water if compared with high saline soil. The saline soil has high concentration salts which is necessary to use more water to leach the salt away from the root zone. If the salinity is extremely high, requiring more than traditional water leaching, the washing process may need to be repeated several times. (Hoffman, G. J. 1986; Burt & Isbell, 2005).

- *B-3- Soil physical and chemical properties*

The osmotic potential is most affected with salt when the salt concentration is increasing in the soil. Because of reducing water absorption by plant. Furthermore, they may influence water viscosity, inhibiting its movement within the soil and reducing the effectiveness of leaching excess salts from the soil.

On the other hand, it impacts the salt balance in the soil. Excessive leaching of salts without consideration of the salt balance may lead to significant loss of divalent nutrients, such as calcium and magnesium. This can cause soil structure deterioration (due to the predominance of sodium) and exacerbate the salinity problem in the long term (Yadav et al., 2011).

- *B-4- Effect on salt movement during leaching*

Soil salinity controls the extent to which slats can be moved to great depths in the soil. Suppose the soil has a high salt concentration. In such cases, it is challenging to reach a specific depth, especially in soils with poor permeability or layers that accumulate and hinder the vertical movement of water. In dry areas, the leaching process may lead to the re-collection of salts on the surface if there is not enough water to push them to greater depths. This occurs due to water evaporation, which leaves the salts back on the surface.

➤ *Groundwater Level*

The groundwater level plays a crucial role in removing salts from the soil, which depends on the interaction between the groundwater level and water movement through the soil (Shi et al., 2021). Here is how the groundwater level affects this process:

The soil is relatively dry when the groundwater level is low, allowing water added from irrigation water and rainwater to move downward. The lowered movement of water can transport salts away from the root zone, reducing the concentration of harmful salts in the surface layer of the soil. However, when the groundwater level is high, the vertical movement of water is limited, reducing the efficiency of washing salts. In some cases, the opposite can occur, especially in hot regions, where there is a significant difference in the water-holding capacity of the surface layer's soil particles due to dryness and evaporation compared to the soil layer near the groundwater level. Thus, the groundwater rises due to the capillary property being loaded with salts, which increases the accumulation of salts on the soil surface.

Therefore, to maintain or reclaim agricultural soil, the groundwater level must be moderate or far away so that the soil can drain excess water and facilitate the filtration of salts from the upper layers.

➤ *Weather*

Weather plays a crucial role in regulating the salt-leaching process from the soil, particularly during the reclamation of saline lands. Rain is the main natural source of water that can leach salts from soil. Heavy and continuous rainfall helps water flow downward, facilitating the removal of salts from the root zone. In arid regions, rainfall may be insufficient to carry out this process naturally, necessitating irrigation. The evaporation rate in high-temperature areas increases when the humidity is relatively low. In conditions of high atmospheric humidity, evaporation from soil decreases, helping to retain water longer in the soil and enhancing the effectiveness of salt leaching (Li et al., 2018).

To achieve effective leaching, the irrigation water used for leaching must be adjusted to match the surrounding environmental conditions and salinity levels. The LF is adjusted with the Evapotranspiration (ET) rate. The ET rate measures water loss from the soil and plant surface through evaporation and transpiration, collectively referred to as ET (Kharaka & Otton, 2007). The ET increases with increasing temperature, while it decreases with increasing humidity (Prathapar et al., 1992). ET is significantly influenced by environmental conditions, which play a key role in the ability of LF to perform infiltration effectively. Therefore, irrigation volumes must be adjusted based on ET to ensure adequate irrigation water availability for LF under the current environmental conditions. Important methods used to calculate ET include the Blaney-Criddle method, the Penman-Monteith method, and pan evaporation (Pan evaporation) (Sharma & Minhas, 2005). However, these methods require a lot of data and parameters, making their practical implementation at the farmer level a significant challenge. LF systems often fail to achieve the desired

ISSN No: -2456-2165 https://doi.org/10.38124/ijisrt/25sep1363

infiltration goal in saline soils if they are not adjusted to the prevailing environmental conditions.

VI. EQUATIONS FOR CALCULATING THE LEACHING FRACTURE OR LEACHING DEPTH

The most empirical equations have been collected from the literature review to estimate the leaching depth or filtration fraction to compare their parameters, as follows:

- Reeve, 1957

$$EC_f = \frac{\left(\frac{La}{Ls} - 0.15\right) * EC_i}{5} \quad \dots (1)$$

where:

EC_f: electrical conductivity-final in the soil (dS m^{-1}).

EC_i: electrical conductivity-initial in the soil (dS m^{-1}).

La: leached water depth (cm).

Ls: reclaimed soil thickness (cm).

- *Volobuyev, According to Palácios, 1969*

$$EC_f = EC_i * 10^{-\left(\frac{L}{\alpha}\right)} \quad \dots (2)$$

where:

L: depth of water added to the soil for salt leaching (mm).

α: coefficient from several variables (chloride content and soil texture).

To calculate the parameter α in the Volobuyev equation:

The coefficient α is empirically determined and depends on two factors:

- Soil texture (e.g., sandy, loamy, clayey).
- Chloride content in the soil or irrigation water.
- These ranges are illustrative; exact values depend on local conditions (Palácios, 1969; modern adaptations in Shiri et al., 2020).
- Field Calibration:
- Conduct field trials by applying a known leaching depth (L) and measuring the resulting ECf. Rearrange the equation to solve for α:

$$\alpha = \frac{-L}{\log_{10}\left(\frac{EC_f}{EC_i}\right)}$$

- *Kovda (1973).*

$$d = \left({}^{Pv}/_{100}\right) * D = \left(W_{fc} - W_{iw}\right) * \rho b * D \quad \dots (3)$$

Where:

d: leaching water depth (cm).

W_{fc}: moisture weight percentage at field capacity (%).

W_{iw}: weight moisture, before washing (%).

ρb: bulk density of Soil (gm cm^{-3}).

Pv: volumetric humidity (%).

D: depth of soil (cm).

- *Rhoades & Merrill (1976)*

$$LF = ECw \div (5ECe - ECw) \quad \dots (4)$$

where:

ECw: salinity of irrigation water (dS m^{-1}).

ECe: soil salinity of saturation extract describes the tolerable salinity for a crop (dS m^{-1}).

- *Jury et al., 1979*

$$C = 0.8 * C_O * \theta * \frac{D_s}{D_e} \quad \dots (5)$$

where:

C: salt concentration in the soil solution (after reclamation), in (mg L^{-1}).

Co: salt concentration in the soil solution (before reclamation), in (mg L^{-1}).

θ: volumetric of soil moisture (cm^3 cm^{-3}).

D_s: soil depth to be reclaimed (cm).

D_e: water depth to be applied to the soil (cm).

- *Hoffman (1980).*

$$C = C_O * K * \frac{D_s}{D_e} \quad \dots (6)$$

Where:

K: constant, varying with the soil texture and the water application method.

Use empirical values from studies (e.g., [Hoffman et al., 1983]; [Shaygan & Baumgartl, 2020]) in Table 2.

ISSN No: -2456-2165 https://doi.org/10.38124/ijisrt/25sep1363

Table 2 Shows Experimental Values of K.

Soil Type	Irrigation Method	Typical K Range
Sandy	Flood	1.3-1.7
Loam	Sprinkler	1.0-1.2
Clay	Drip	0.7- 0.9

➢ *Ayers and Westcot (1994) state as follow:*

$$LF = \frac{EC_i}{EC_d} = \frac{EC_i}{5EC_e - EC_i} \quad \ldots (7)$$

Where:

EC_i: electrical conductivity of water irrigation.

EC_d: drainage water.

EC_e: saturated soil extract in (dS m^{-1}).

➢ *Cordeiro, 2001*

$$EC_f = EC_i * 10^{-\left(\frac{L}{2.025 * P * (\frac{70 - ECr}{EC_i - EC_r})}\right)} \quad \ldots (8)$$

where:

L: depth of water applied to the soil for leaching the salt (mm).

P: soil depth to be reclaimed (cm).

ECr: electrical conductivity of water leached (dS cm^{-1}).

➢ *Owen et al., 2008*

$$\text{Leaching fraction} = \frac{\text{Effluent Volume (ml)}}{\text{Influent Volume (ml)}} \quad \ldots (9)$$

The equations above were summarised in Table 3, which shows the factors studied by researchers in their equations to determine the amount of water required to remove salts from the soil. The more factors there are, the more realistic the results are, which is expected to simulate the field, and thus, it can be applied in all different conditions.

Table 3 Presents the Determination of Parameters Controlling Equations for Leaching Salts from the Soil.

Eq.	**Factors controlling the process of leaching salts from the soil**								
	a) Hydraulic properties of the soil	**b) Depth of soil to be reclaimed**	**c) Moisture content of soil**	**d) Initial soil salinity**	**e) Desired soil salinity**	**f) Salinity of leaching water**	**g) Depth of water applied**	**h) Groundwater level**	**i) Weather**
Reeve (1957).	X	√	X	√	√	X	√	X	X
Volobuyev, according to Palácios (1969).	√	√	X	√	√	X	√	X	X
Kovda, 1973.	√	√	√	X	X	X	√	X	X
Rhoades & Merrill, 1976.	X	X	X	√	√	√	X	X	X
Jury et al., 1979.	X	√	√	√	√	X	√	X	X
Hoffman, 1980.	√	X	X	√	√	X	√	X	X
Ayers and Westcot (1994).	X	X	X	√	√	√	X	X	X
Cordero (2001).	X	√	X	√	√	√	X	X	X
Owen et al., 2008.	X	X	X	X	X	X	√	X	X

VII. LF APPLICATION

Extraction to provide more profitable situations for seed germination or plant establishment is a crucial strategy for reclaiming salt-affected lands, particularly in arid and semi-arid environments. In natural ecosystems, the concentration of soluble salts in the topsoil increases with evaporation and the onset of arid conditions, which can also lead to salt deposition. Without extraction, salts accumulate on the soil surface (Hoffman et al., 2007) and can limit seed germination and plant establishment. Salt extraction aims to reduce solutes from the upper layers of the soil. Extraction of soluble salts

ISSN No: -2456-2165 https://doi.org/10.38124/ijisrt/25sep1363

from soils by rainfall may occur under natural ecosystem conditions (Pariente, 2001), where the soil has the potential for deep drainage. Salts can be return to the soil surface in dry condition if the rainfall is low. The rainfall plays important role to redistribution salt in the soil profile. (Pariente, 2001). The low hydraulic conductivity values in soils with different layers or horizons can restricts soil infiltration and downward water movement. (Hoffman et al., 2007; Harker & Mikalson, 1990; Shaw & Thorburn, 1985). Some soil physical properties such as hydraulic conductivity, infiltration rate, and drainage exhibit low values in sodium -saline soils. (Rengasamy et al., 1991; Shainberg et al., 1984). Improving the soil physical quality leads to create a a better condition for seed germination through enhance soil infiltration and soil hydraulic conductivity. Enhancing water and air movement in the soil pores reflect improving soil physical quality. (Marshall et al., 1996). The Varity pores size such as the macropores are considered the key element to solute and water transport in the soil. Although macropores may contribute only a very small amount to the soil's total porosity, they significantly affect the total water movement through the soil. Large pores increase the downward water flow and allow greater infiltration into the soil. Increased water volumes can transport the solutes deeper into the soil profile, increasing infiltration (Beven & Germann, 1982). The saline soils, which have sodium, are poorly aggregated and have an inadequate pore system (i.e., lack of macropores or inter-pore connectivity), and are unable to create suitable conditions for salt infiltration, especially where rainfall is insufficient and irregular, as in arid (semi-arid) environments. Reclamation strategies can be effective in improving the soil pore system and facilitating the leaching of salts, thereby promoting plant germination and revegetation.

VIII. RESEARCH GAPS, STATUS, AND FUTURE TRENDS

The volume of water required for soil reclamation is calculated based on the initial soil salinity, the desired final salinity level, the type and depth of the soil to be reclaimed, the method of water application, and the salt concentration in the wash water (Dias, 2001). Soil reclamation can be accomplished using various strategies to implement each method successfully. A significant point of consideration is the provision of an adequate soil drainage system (Qadir et al., 2000). Salt leaching tests, then, should be conducted on a limited area, and leaching curves should be prepared to obtain more accurate estimates. The leaching curves relate the ratio of the actual salt content to the initial salt content in the soil to the depth of the extraction water per unit of soil (Fig. 4).

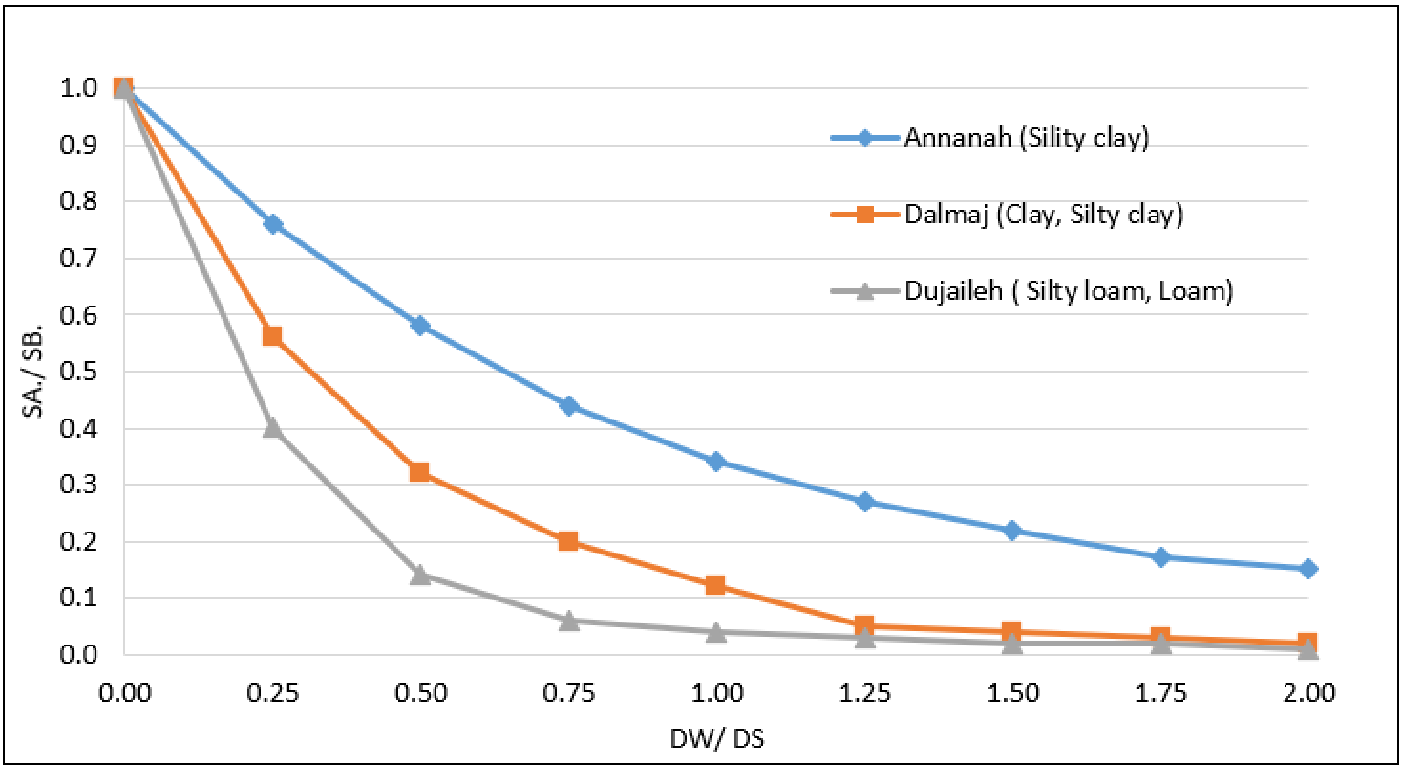

Fig 4 Typical Leaching Curves for Soils in Iraq (DW = Net Depth of Leaching Water; DS - Depth of Soil Profile Concerned; SA. = Required Salinity level; SB. = Initial Salinity Level) (Dieleman, 1963).

Nevertheless, the success of each reclamation method depends on multiple factors, such as the types and concentrations of salts present, the availability of high-quality water (with low electrolyte concentration) for reclamation, the texture of the topsoil, the quality and level of groundwater, the volume of soil to be reclaimed, the characteristics of the salt-affected soil, the type of crops grown after reclamation, the prevailing climatic conditions, the time frame allowed for reclamation, and cost-effectiveness (Mahanta et al., 2015; Qadir et al., 2000). In some cases, these methods can be applied individually or in combination with other strategies to achieve a successful reclamation program (Shankar & Evelin, 2019). However,

ISSN No: -2456-2165 https://doi.org/10.38124/ijisrt/25sep1363

these methods cannot be generalised under different circumstances.

IX. MODELS AS PREDICTIVE TOOLS FOR IDENTIFYING EFFECTIVE RECLAMATION PRACTICES

To determine an effective reclamation strategy, a model can simulate the transport of solutes, account for cation exchange, mineral dissolution, precipitation, and changes in soil hydraulic conductivity resulting from modifications to soil chemistry, as well as the interrelationships among all these factors (Gonçalves et al., 2006). Several soil hydrogeochemical models can be used to simulate and predict the transport of solutes in soil profiles (porous media), thus, the success of reclamation techniques.

Furthermore, the success of reclamation practices depends on understanding the interaction between plants, soils, and climate. Thus, numerical models can simulate scenarios and integrate climate (temperature, humidity, evaporation), soil (chemical and physical properties), and plant characteristics (Shaygan & Baumgartl, 2020). Thus, reclamation practices for saline soils can be evaluated when all relevant climate and soil conditions are accurately applied and determined using the appropriate model. This also leads to no more costs due to improved screening methods during development. Field experiments on solute transport are typically based on simple functional relationships and cannot fully account for spatial and temporal variability at the field scale (Shaygan et al., 2018a; Rasouli et al., 2013; Gonçalves et al., 2006).

Many tools simulate water movement and solute transport in soil, such as Numerical model processes (Predicting Agricultural Solute Transport in Soils (PASTIS), Soil Water Atmosphere Plant (SWAP), Leaching Estimation & Chemistry (LEACHM), MACRO, HYDRUS-1D, HP1-PHREEQC, HYDRUS-2D, HYDRUS-3D, Finite Element Subsurface Flow (FEFLOW)), Machine Learning Models (Artificial Neural Networks (ANNs), Support Vector Machines (SVM), Adaptive Neuro-Fuzzy Inference Systems (ANFIS), and Multiple Linear Regression (MLR)).

Machine learning is one of the artificial neural networks which can be widely used in in different filed of soil science such as simulation and optimization models. Many research have been applied different types of (ANN) to estimate soil infiltration rates, soil erosion rates, soil hydraulic conductivity (Harris & Boardman, 1998; Rosa et al., 1999). (Jain & Kumar, 2006) estimated soil infiltration rates in artificial neural network, and (Schaap et al., 2001; Ghanbarian-Alavijeh et al., 2010) was used the artificial neural networks to estimate hydraulic conductivity. The artificial neural network have been applied in multidiscipline in hydrological processes (Lazarovitch et al., 2009b), environmental prediction (Anctil & Rat, 2005), and soil microbiology which was applied to predict soil microbial processes (Kavuncuoglu et al., 2018).

In addition, another numerical models which can be used in solute transport process are LEACHM (Hutson & Wagenet, 1995), VADOSE/W or SEEP/W, UNSATCHEM (Suarez & Šimunek, 1997), and HYDRUS (Šimunek et al., 2008; Šimunek et al., 2013). Among these numerical models which can evaluate land reclamation and find the impact of soil chemistry on the soil hydraulic conductivity are UNSATCHEM and HYDRUS (Reading et al., 2012; Shaygan et al., 2018a). Furthermore, the HYDRUS package is considered an effective model due to including the UNSATCHEM, which can model ion chemistry and carbon dioxide (Šimunek et al., 2008).

The algorithm of machine learning and HYDRUS framework models were simulated to find the most accurate method to predict the soil water retention characteristic curve (SWRC). The machine learning algorithm has many types of models such as artificial neural networks (ANNs), support vector machines (SVMs), adaptive neuro-fuzzy inference systems (ANFIS), and multiple linear regression (MLR). The models are more flexible and without explicit programming. On the other hand, the best simulation performance to present EWDrz, with an RMSE value of 0.66 mm, an MBE value of 0.81 mm, and an EF value of 0.99. It was followed by the SVM and ANFIS models is the HYDRUS-2D model. The HYDRUS 2D provides more accurate EWDrz results if compared with MLR model. Furthermore, the models which have poor performance in relative to MLR are SVM1 and ANFIS1 models. (Karandish & Šimůnek, 2016).

Many researchers have mentioned that salt leaching and soil solute transport can be evaluated by using machine learning and HYDRUS 2/3D models (Gonçalves et al., 2006; Zeng et al., 2014; Suarez & Šimunek, 1996). These models can be able to implement to improve amelioration strategies (Shaygan et al., 2018a; Shaygan et al., 2018b; Shaygan & Baumgartl, 2020; Suarez & Šimunek, 1996; Corwin et al., 2007). For instance, a hydro-geochemcial model within HYDRUS model is an accurate model which can be applied in various rainfall patterns and evaporation situations to predict the solute transport (Zeng et al., 2014). (Shaygan et al., 2018a, 2018b; Shaygan & Baumgartl, 2020) were verified that the hydro-geochemcial model can be applied in a salt-influenced soil after adding some physical amendments such as find sand and plant residue. The above suggests the applicability of using the hydrogeochemical model to assess a reclamation approach under natural climatic conditions. Water movement and dissolved substances in soil are widely assessed using a numerical model (e.g., HYDRUS).

An identifying effective reclamation is critical to validate the numerical models in saline soils because it is necessary to verify and calibrate after use them for accuracy. Shaygan et al. (2018b) noted that using soil amendments with sand and wood chips can enhance aeration and reduce salt infiltration. Vertical experiments were used to simulate water and salt movement, and the model results were verified using HYDRUS software. The study demonstrated that unamended soils exhibit better salt infiltration and that soil density modification is the most effective factor for the reclamation of saline soils. This process demonstrates how numerical

ISSN No: -2456-2165 https://doi.org/10.38124/ijisrt/25sep1363

models can serve as predictive tools for complex reclamation scenarios, enabling decision-makers to implement effective soil management practices.

X. CONCLUSION

This review paper is concluded that the salinization issue can be combated and coexisted with. In future, it is necessary to use new comprehensive methods for using irrigated saline water for irrigation and reclamation. An integrated approach should be use to restoring the saline-affected soils to address, instead of expressing on saline soil restoration under certain conditions. The important element in conducting experiment field is using one of the most reliable software such as HYDRUS 2/3D which can simulate the data. The results, then, can be calibrated to be ore applicability in the real saline areas under different conditions. Future maintenance and management measures for those soils will be designed.

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