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Review

Reclamation of Salt-Affected Land: A Review

Mandana Shaygan [1,*] and Thomas Baumgartl [2]

[1] Centre for Water in the Minerals Industry, The University of Queensland, Brisbane, QLD 4072, Australia
[2] Geotechnical and Hydrological Engineering Research Group, Federation University, Churchill, VIC 3841, Australia; t.baumgartl@federation.edu.au
* Correspondence: m.shaygan@uq.edu.au; Tel.: +61-7-3346-4052

Abstract: Reclamation of salt-affected soil has been identified by the FAO as being critical to meet the needs to increase agricultural productivity. This paper reviews commonly used reclamation methods for salt-affected soils, and provides critical identifiers for an effective reclamation practice of salt-affected soil. There are widely used methods to reduce salinity and sodicity of salt-affected soils, including salt leaching, addition of amendments, revegetation using halophytes and salt scrapping. Not all reclamation techniques are suitable for salt-affected land. The reclamation strategy must be tailored to the site, and based on understanding the soil, plant and climate interactions. On some occasions, a combination of techniques may be required for reclamation. This can include salt scrapping to remove salts from the surface soil, the addition of physical amendments to improve soil pore systems and enhance salt leaching, followed by amelioration of soil by chemical amendments to preserve soil physical conditions, and then halophyte establishment to expand the desalinization zone. This study reveals that soil hydro-geochemical models are effective predictive tools to ascertain the best reclamation practice tailored to salt-affected land. However, models need to be calibrated and validated to the conditions of the land before being applied as a tool to combat soil salinity.

Keywords: chemical soil amendments; physical soil amendments; modelling; salt leaching; salt scrapping; soil ripping

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1. Overview of Soil Salinity Problem

Approximately one billion hectares of soil in the world are estimated to be affected by salinity [1,2]. Salinity can be either natural, or related to land use activities such as land clearing, mining [3], oil extraction [4], agricultural activities and dry land salinity [5]. Soil salinization can be affected by climate, soil type, irrigation, depth to groundwater and salinity of water sources, as well as land management practices [6,7]. Salinity is more evident in arid and semi-arid climates as the amount of rainfall is not adequate to leach salts from the surface soil [8], and in some instances, the leaching capacity of the soil is not sufficient to leach salts from the surface soil [9].

Salt-affected soils are generally divided into three categories: soils with high electrical conductivity from a saturation extract (ECe) > 4 dS m^{-1}, pH < 8.5 and exchangeable sodium percentage (ESP) and <15, which are considered saline soils [10], such as found at a site near Seville, in Spain [11]. Saline-sodic soils, such as found at an oilfield near Eromanga, Australia [12], are defined by ESP in high levels (>15), pH < 8.5 and high electrical conductivity (ECe > 4 dS m^{-1}), and if the soil has an ECe < 4 dS m^{-1}, pH > 8.5 and ESP > 15, it is classified as a sodic soil [10], such as the research farm in Pindi Bhattian, Pakistan [13].

Salinization significantly impacts soil, vegetation and ecosystem functions [1]. Although some moderate to high salt-tolerant plants can grow and survive in highly saline environments [14–16], salinity in the plant root zone will most likely result in the inhibition of plant establishment and growth. The probability of survival for most plant species due to the limitations in plant water uptake, resulting from osmotic implementation [17] and low soil water potential [18–21], will be highly impacted. Salinity can also result in a water deficit and turgor loss in plant cells [15], and interfere with plant metabolism through ion toxicity and ion imbalance [22–26]. Salt crust, which is an inhibiting factor for plant germination and establishment in arid environments, can be created on soil surfaces because of the high evaporation associated with the upward movement and precipitation of soluble salts [27].

Plant establishment and growth can also be limited due to poor soil physico-chemical properties from saline-sodic conditions [28,29]. High exchangeable Na^+ concentrations negatively affect soil structure. This is associated with a reduction in soil hydraulic conductivity, infiltration and aeration [28–31], mostly as a result of increased swelling and clay dispersion [30,32]. Reduction in infiltration and hydraulic conductivity in dry climates also leads to a reduced storage and provision of water to plants [33]. Poor soil structure can also influence drainage and salt leaching [34] and restricts seed germination and plant establishment.

Salinity issues can often be found associated with mining activities as a result of a lack of availability of suitable substrate for reclamation. The rehabilitation of these salt-affected lands appear necessary, as these lands can be (re-)used as agricultural resources [1,35] such as producing fodder for livestock. It also provides an opportunity to re-establish plants [12,36,37] and stabilise the landform. However, salinity and sodicity and their consequences can limit plant establishment, revegetation and hence land rehabilitation. Therefore, adapted soil reclamation strategies are required to firstly provide more favourable conditions for plant establishment (revegetation), and enable conditions for successful land rehabilitation.

The aim of this review is to highlight suitable techniques for the reclamation of salt-affected land. This study firstly provides insight into common reclamation strategies that have been widely used for saline land. This study then discusses an approach for identifying an appropriate method for salt-affected soil reclamation.

2. Saline-Sodic Soil Reclamation Techniques

2.1. Reducing Salinity by Leaching

Leaching to obtain more favourable conditions for seed germination or plant establishment is an important strategy for reclamation of salt-affected land, almost notably for arid and semi-arid environments. In natural ecosystems, the concentration of soluble salts in surface soils increases with evaporation and increased arid conditions and may also lead to salt precipitation. Without leaching, salts accumulate at the soil surface [33] and can limit seed germination and plant establishment. The aim of salt leaching is to reduce the solutes from the upper layers of the soil. Leaching of soluble salts in the soil may occur from rainfall in the natural condition/ecosystem [38] where the soil has the potential for deep drainage. In this context, the amount and distribution of rainfall play an important role in salt leaching, as extended periods of dry conditions and reversing the direction of solute flux can return salts to the surface soil [38].

Soils with layers or horizons of low hydraulic conductivity can limit downward water movement and prevent adequate leaching [33,39,40]. Saline-sodic soils typically show poor soil physical conditions which are associated with low hydraulic conductivity, infiltration, and drainage [28–31]. Adapted practices are required to improve soil physical conditions to enhance salt leaching and create more favourable conditions for seed germination.

Soil pores create a condition for the movement of water and air within the soil [34]. Among the different sizes of soil pores, macro-pores play an important role in water and solutes movements [41]. Even though macro-pores may contribute only a very small amount to the total porosity of a soil, they have a very significant effect on the overall water movement through soils [41]. Macro-pores increase downward water flow and allow higher infiltration into the soil. Increased volumes of water are able to transport dissolved solutes deeper into the soil profile, and increase leaching [41]. Saline- sodic soils, which are poorly aggregated and have an inadequate pore system (i.e., the lack of macro-pores or connectivity among the pores), cannot create the appropriate conditions for salt leaching, particularly where there is insufficient and irregular rainfall such as in (semi-) arid environments. Reclamation strategies will be beneficial to ameliorate the soil pore system and assist with leaching salts and thus facilitate plant germination and hence revegetation.

2.1.1. Addition of Organic Amendments as Ameliorant

Organic matter is one of the fundamental factors in the soil structure/formation of aggregates and the pore system, as well as the soil chemistry, due to its high specific surface area with colloidal characteristics [34,42]. The presence of organic matter, as a binding agent between and within aggregates [34,42,43] can increase the stability of soil aggregates [44] and improve water holding capacity [45–47], infiltration, water passage [11,45,47] and the soil pore system in general [9,43]. Improvement in salt leaching through the addition of organic amendments has been reported by several authors [48–53]. The application of organic amendments to saline soils is promising for soil chemical amelioration such as Na^+ leaching, which decreases the ESP and EC of the soil [11,45,47,54]. For instance, Wahid et al. [47] concluded that an addition of 3% organic amendment (farm yard manure, clover hay and wheat straw) was effective in the reduction of EC and pH in a saline-sodic soil. However, in some instances, manures (i.e., cattle manure and poultry manure) and composts contributed to an increase in soil salinity and sodicity, as they provided a source of salt [55–57]. This suggests that not all manures and composts may be suitable for the reclamation of salt-affected land.

Soil amelioration using organic amendment depends on the nature of organic material [47]. For example, the addition of organic amendments, such as manure and compost, may decrease pH (<1 pH-unit average decline) of the soil [47,49] and the application of these organic amendments may not be beneficial for the reclamation of salt-affected soils with a neutral pH condition. In some instances, soils that had high organic matter content and low hydraulic conductivity due to the mobilization of organic colloids clogged the soil pore system [58]. However, the reduction in the hydraulic conductivity could also be affected by other intrinsic factors such as soil texture [58]. Although the addition of various organic amendments such as compost, fertilizers, crop residue and manures, and their success in the reclamation of saline-sodic soils has been documented [11,47–53,59], the type and application rate of amendments to be used for soil depends on climate, soil biological and chemical factors. It must be noted that salinity under arid conditions can reduce the efficacy of the supplement materials on soil's physico-chemical properties.

Plant residues can be used as an organic amendment for improving soil physical conditions [11,51,52,60]. An application of hay to the surface of brine-contaminated soil, in Osage County, USA, appeared to have made a significant impact on desalinization [50]. However, a two-step reclamation strategy was involved in the study. In one step, a subsurface drainage system was installed, and in another step, hay was added and the soil was irrigated [50]. Harris et al. [50] concluded that hay increased permeability and enhanced salt leaching. Shaygan et al. [61] also concluded that the addition of 20% wood chips to a saline-sodic soil can decrease soil salinity by approximately 5 dS m^{-1}. The addition of wood residue also increased the leaching of the bentonite mine spoil, through improving the physical condition of the spoil which enabled vegetation establishment [62]. The addition of wood chips may be beneficial for ameliorating saline-sodic soil physico-chemical conditions as it can reduce upward movement of salts as well as improve salt leaching [63].

The longevity of organic ameliorants in soil should be considered when selecting the ameliorant type. Some organic ameliorants such as compost decomposes in the soil quicker than plant residues such as wood chips. This characteristic may make these ameliorants less beneficial and/or less economically desirable particularly when the long-term effect on soil physical improvement is sought. Therefore, from the literature review, it can be concluded that the addition of plant residue (e.g., wood chips) is possibly a better option to improve saline-sodic soil physico-chemical conditions and create conditions for seed germination.

2.1.2. Soil Texture and Leaching Capacity

Soil texture determines soil physical properties such as pore system, water holding capacity and drainage [64]. Most physico-chemical reactions of the soil are reliant on the amount and type of clay minerals [34]. The colloidal nature, negative surface charge and highly specific surface area of clay minerals creates high sorption capacity [64]. Aggregation stability improves with an increase in clay content when the soil has high sand content [42,65]. The type and amount of clay present in the soil are key factors in aggregation development and/or stability [34,42] as low activity clays such as kaolinite tend to decrease aggregate stability [42].

Clay minerals can affect the creation of moderate to large pores [66]. Macro-pores, which are preferable for drainage/leaching, are normally formed by roots, fauna and by soil swelling and shrinking as the soil wets and dries [41,67,68]. Expanding clay acts as a key factor in soil physical properties as it swells in wet conditions, and it shrinks as it dries [69,70]. Shrinkage creates cracks, breaking the soil mass into fragments of various sizes, from small aggregates to large blocks [69]. Aggregate size and its distribution is controlled by its soil properties [71]. Cracks can provide paths for water infiltration [72]. Creation of cracks may ameliorate the poor soil physical condition in low porosity soils as they create drainable pore space in the soil [73]. Cracks can assist water movement through the soil profile and enhance salt leaching. However, water flow through the soil cracks may limit salt leaching from the soil matrix [73] since water may be distributed in the soil profile through the cracks and dependent on the type of rainfall event may not wet uniformly the whole soil matrix [68]. However, the limitation in salt leaching through cracks depends on the geometry (depth and width) of the created cracks [74]. Furthermore, the flow may confine the salt leaching to cracks only, but is also affected by rain quantity and intensity, the surface soil moisture content and soil texture [74]. In a study on the effect of clay (bentonite) on salt leaching, Shaygan et al. [61] found that the addition of 2.5% bentonite (wt/wt) to a saline-sodic soil resulted in a 92% reduction in soil Na^+ content under the specific environmental conditions.

Alteration of a fine textured substrate by incorporating coarse particles such as sand improves conditions for the migration of water through the profile, as they can alter the pore size distribution towards a larger proportion of coarse pores [34]. During leaching, water does not flow uniformly through a soil profile, but preferentially through coarse or macro-pores [75]. As a result, soils with high coarse particle or sand content, which is linked with a higher proportion of coarse pores, are known to be preferable for solute transport and salt leaching [54,76]. However, Hartmann et al. [77] reported that an increase in water flow/hydraulic conductivity reduced cation exchange in the soil due to a reduction in percolation time and the concentration to preferential pathways. Hartmann et al. [77] concluded that with increasing the percolation time, the accessibility of exchange surfaces increases and the time for chemical reactions is reduced. This can affect the success of salt leaching in the soil profile since high rates of cation exchange can result in the leaching of large amounts of salts from the soil. Ghafoor et al. [78] also reported that reclamation is more effective in saline-sodic soil with a high CEC. Addition of sand as a soil supplement to improve water movement has been studied for turfgrass establishment [79–81]. A few studies have also noted that sand can affect salt leaching [54,82]. For instance, Rahman et al. [54] reported that sand amendment significantly promoted the desalinization zone when compared to organic and chemical amendments (chicken manure, gypsum, farm yard manure, dry sludge, water hyacinth). Shaygan et al. [61] also showed an addition of 40% fine sand (wt/wt) to a saline-sodic soil can reduce salinity and sodicity by approximately 70% and 40%, respectively, through improving the pore system (increasing total porosity and connectivity among pores) and ion exchange.

2.1.3. Addition of Chemical Amendments

Saline-sodic soils can be reclaimed by using chemical amendments. The typical chemical amendments are gypsum ($CaSO_4$), lime ($CaCO_3$), sulphuric acid (H_2SO_4), hydrochloric acid (HCl) and nitric acid (HNO_3) [83]. Gypsum and lime containing calcium (Ca^{2+}) can substitute sodium ions at the cation exchange sites during leaching [84,85]. This process can result in flushing out of the sodium from the root zone. The beneficial use of gypsum and lime for the reduction of salinity and improving soil structure has been shown in several studies [49,84,86–90]. For instance, Goncalo Filho et al. [84] concluded that applying 38.7 t ha^{-1} gypsum can substitute 20% of the ESP in a saline-sodic soil (pH: >8.5; ESP: >22.2%; EC: >4 dS m^{-1}) located in semi-arid regions of northern Brazil.

Chemical amendments such as sulphuric acid [89,91–94] and hydrochloric acid [95–97] have been applied to dissolve calcite and thus activate calcium (Ca^{2+}) to be exchanged with sodium (Na^+) in calcareous saline-sodic soils. As an example, Amezketa et al. [93] indicated that the addition of sulphuric acid was the most effective treatment in leaching and reducing salinity in comparison with gypsum amendments. However, the application of acidic amendments can lower soil pH, thus, their applications need some consideration.

2.1.4. Soil Ripping

If soil compaction is a problem, which is normally a consideration in sodic soils, ripping can be used as a method to reduce the compaction and assist with salt leaching and thus reclamation [12,98]. Soil ripping up to a depth of 15 cm has been reported by Shaygan et al. [99] as a successful method of saline-sodic land reclamation. However, to achieve long-term improvement in soil physical conditions, particularly in macroporosity, ripping should be combined with chemical ameliorates (i.e., Ca^{2+} amendments), particularly for sodic soils [100] to stabilize the newly formed pore structure. The soil also requires protection from re-compaction during irrigation [100].

2.2. Halophytes for Phytoremediation

Saline-sodic soils can be reclaimed through revegetation, which uses a plant-assisted approach to ameliorate the soil [101]. This approach relies on plant, soil and hydrological interactions. The rehabilitation through plants (phytoremediation) can also be managed productively, as the plants can often be used as fodder [102]. In some instances, phytoremediation of saline-sodic land can result in improvements comparable with engineering methods [103]. Qadir and Oster [103] compared the results from 14 experiments [53,83,86,88,104–111] and concluded that applying gypsum reduced sodicity but was only effective in the surface layer. However, phytoremediation resulted in amelioration throughout the whole plant root zone and was more effective [103]. It should be noted that the application of gypsum can increase the soil salinity initially. However, the increase in soil hydraulic conductivity resulting from the application of gypsum allows salt to be leached and reduces salinity.

Saline-sodic soils can be remediated through revegetation using halophytes [101]. Halophytes, which represent approximately 1% of global flora biodiversity [1], can survive, live and complete their life cycle in high concentrations of salt (at least 200 mmol NaCl) [112,113]. Some species of halophytes (e.g., *Salicornia europaea* and *Salicornia bigelowii*) would not grow adequately in the absence of added NaCl [114], and the growth of some species of halophytes is stimulated by moderate salinity conditions (50–250 mmol NaCl) [112]. Several researchers have reported the success of saline-sodic soil reclamation using halophytes [27,110,115–123]. Species such as *Suaeda maritima*, *Suaeda portula-castrum*, *Suaeda salsa*, *Suaeda fruticosa*, *Atriplex nummularia* and *Atriplex prostrata* have been reported to tolerate high levels of Na^+ and accumulate high concentrations of Na^+ in their tissues, making these species effective for the revegetation and reclamation of saline lands [124]. For instance, *Suaeda salsa* removed 3090–3860 kg ha^{-1} Na^+ from soil with 15 plants per m^2 density after a period 120 days of growth [118]. Halophyte roots can also ameliorate the soil structure through the creation of pores, which results in improving the water and air flow [123,125].

Typical improvements resulting from reclamation through revegetation of halophytes include:

- Improvement of soil aggregation stability and soil hydraulic properties;
- Deeper reclamation zone compared with other reclamation methods (i.e., gypsum application);
- Improvement of chemical and physical properties of the soils;
- Financial benefits due to a reduction in application of chemical amendments or leaching [103].

Species from the Chenopodiaceae family, which has the highest proportion of halophytic genera with 312 salt tolerant species [112], are considered suitable for revegetation and reclamation as they adjust to and tolerate salt stress better than halophytes from other families such as Poaceae [126]. Halophytic species within the Chenopodiaceae family are widely used for revegetation and land reclamation [27,110,115–123]. In saline conditions, species of the Chenopodiaceae family adjust their shoot osmotic pressure and accumulate large amounts of Na^+ and Cl^-, and so a large proportion of the dry weight of these plants consists of inorganic ions [127]. Some genera of the Chenopodiaceae, including *Atriplex*, which are extremely salt tolerant, have been well studied for their revegetation and land reclamation potential [27,115,117,128]. The potential of *Atriplex* species for revegetation of salt-affected soils has been noted in several studies because of accumulation of salts in their aboveground tissues, particularly in their leaves [26,115,117,129–134]. For example, *Atriplex halimus* accumulated up to 3137 meq kg^{-1} dry wt Na^+ in the shoot tissues after one year of planting [115]. In a study on different species of Chenopodiaceae, Shaygan et al. [12] reported an average of 38.5% and 33% reduction in salinity and sodicity, respectively, for the top 10 cm of saline-sodic soil located in a semi-arid environment.

2.3. Salt Scraping

Saline land can be physically reclaimed by salt scraping to remove the salt crust so that plants can be re-established [128,129]. This must be typically followed by leaching to remove salts including Na^+ from the root zone, and in moderate saline-sodic conditions, applying Ca^{2+} amendments to displace exchangeable Na^+ [33,135–137]. The dynamics of salt precipitation should be considered when salt scraping is considered as a method of saline soil remediation, as a high evaporation rate can move salts upward towards the soil surface and a high rainfall event can leach the salts to deeper depths of the soil profile where salts may not return to the surface soil [99]. Therefore, without interfering with a possible principal cause for the occurrence of a salt crust, this strategy may be limited to specific land and climatic conditions.

3. Identification of the Most Suitable Strategy for Salt-Affected Soil Reclamation

Application of mentioned strategies (leaching, amendments, soil ripping, halophytes, salt scraping) requires a range of resources and conditions, and hence may not be tailored to all salt-affected lands due to a shortage of water and energy resources, high cost as well as climatic conditions. For example, water shortage is of particular importance for reclamation of salt-affected lands in mine sites, as most mine sites are located in remote areas of semi-arid and arid environments [138]. Therefore, the reclamation of most post-mine land mainly relies on natural climatic conditions, rainfall depth and distribution as well as evaporation.

Rapid changes in saline habitat can be caused by climatic conditions. In the presence of sufficient rainfall, a high leaching rate can be created, leading to low concentrations of salts in the root zone [139]. Under arid and semi-arid conditions, evaporation from the soil surface is one of the factors which controls soil salinization, as it can result in returning salts to the surface soil [140]. Upward movement of salts in soils is caused by capillary rise due to evaporation from the soil surface and accumulates salts if no counter balance of downward movement of water exists [140]. The capillary rise, influenced by soil hydraulic parameters, determines the amount of solutes that can be transported [141,142]. Many salt-affected soils are located in (semi-)arid regions where leaching/irrigation is infeasible/limited and high evaporation rates may restore the saline impacts [132]. Therefore, seed germination in arid and semi-arid regions usually occurs after rainfall because of a reduction in the surface soil salinity [113]. Such a pattern results in seed germination and seedling establishment prior to the period of salt stress [27]. Under (semi-)arid climatic conditions, rain events do not occur frequently, so germination may be successful once every several years [143]. Therefore, the relationship (i.e., interaction/overlap) between soil, plant and climate must be considered for identifying the suitability of each remediation strategy (Figure A1).

Leaching is the main remediation technique for salt-affected lands. However, the efficiency of leaching can be restricted by poor soil physical conditions that limit downward water and solute movement into deeper depths of the soil profile. Therefore, the addition of amendments to improve soil physical conditions and thus enhance salt leaching may be required. The type of amendments to be used for improving soil physical conditions depends on the soil chemical conditions, resource availability and cost, as well as climatic conditions. This is particularly important for the reclamation of salt-affected land located in remote areas. To further expand the desalinization zone, phytoremediation using halophytes may be used. Halophytes can increase both the desalinization depth and longevity of the salt extraction rate [144]. However, sometimes the high level of soil salinity as well as inappropriate climatic conditions restrict halophyte establishment [12]. When the climatic conditions and soil conditions are barriers to success for reclamation, a combination of different practices may be required for reclamation. For instance, first salt scrapping, and then the addition of amendments and using soil ripping could be an option to improve the soil physical conditions, thus enhancing salt leaching under natural climatic conditions and providing conditions for halophyte establishment (Figures 1 and 2), which can function as a phytoameliorant by altering the moisture and flux conditions and reduce the transport of slats to the surface. Examples of integrated management of salt-affected soil, which combine amendments and/or reclamation techniques, can be found in the literature [84,99,145–148]. These studies [84,99,145–148] concluded that integrated management of salt-affected soils strengthens soil salinity and sodicity mitigation.

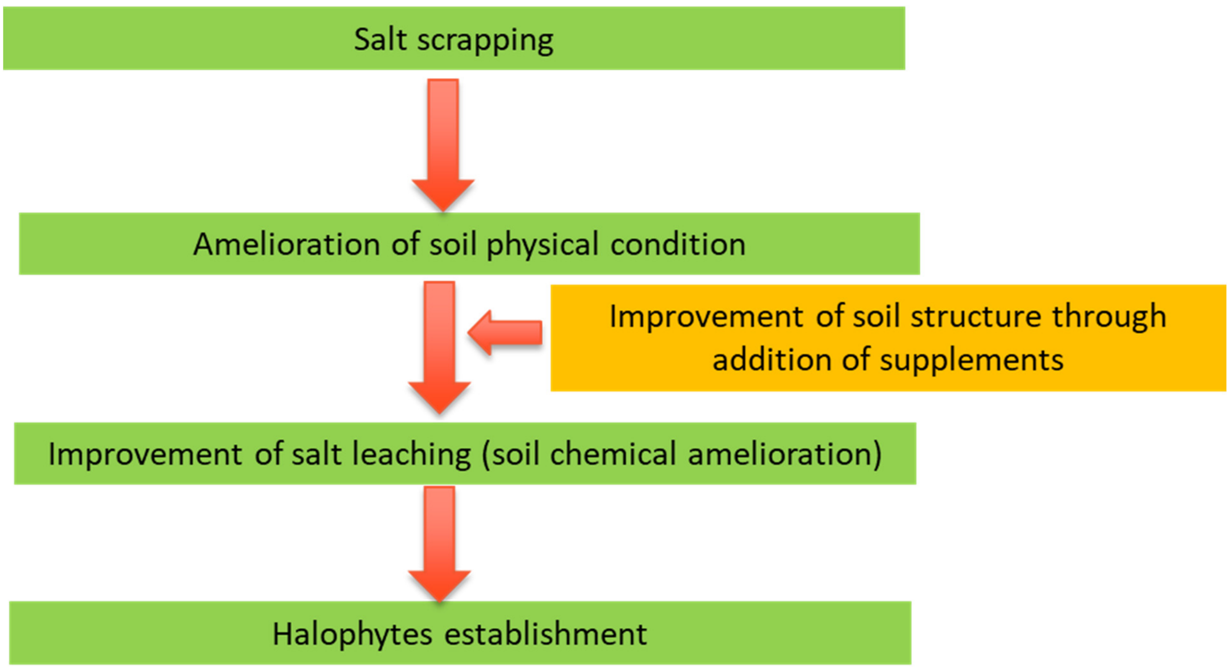

Figure 1. The diagram indicating the techniques required for reclamation of salt-affected land.

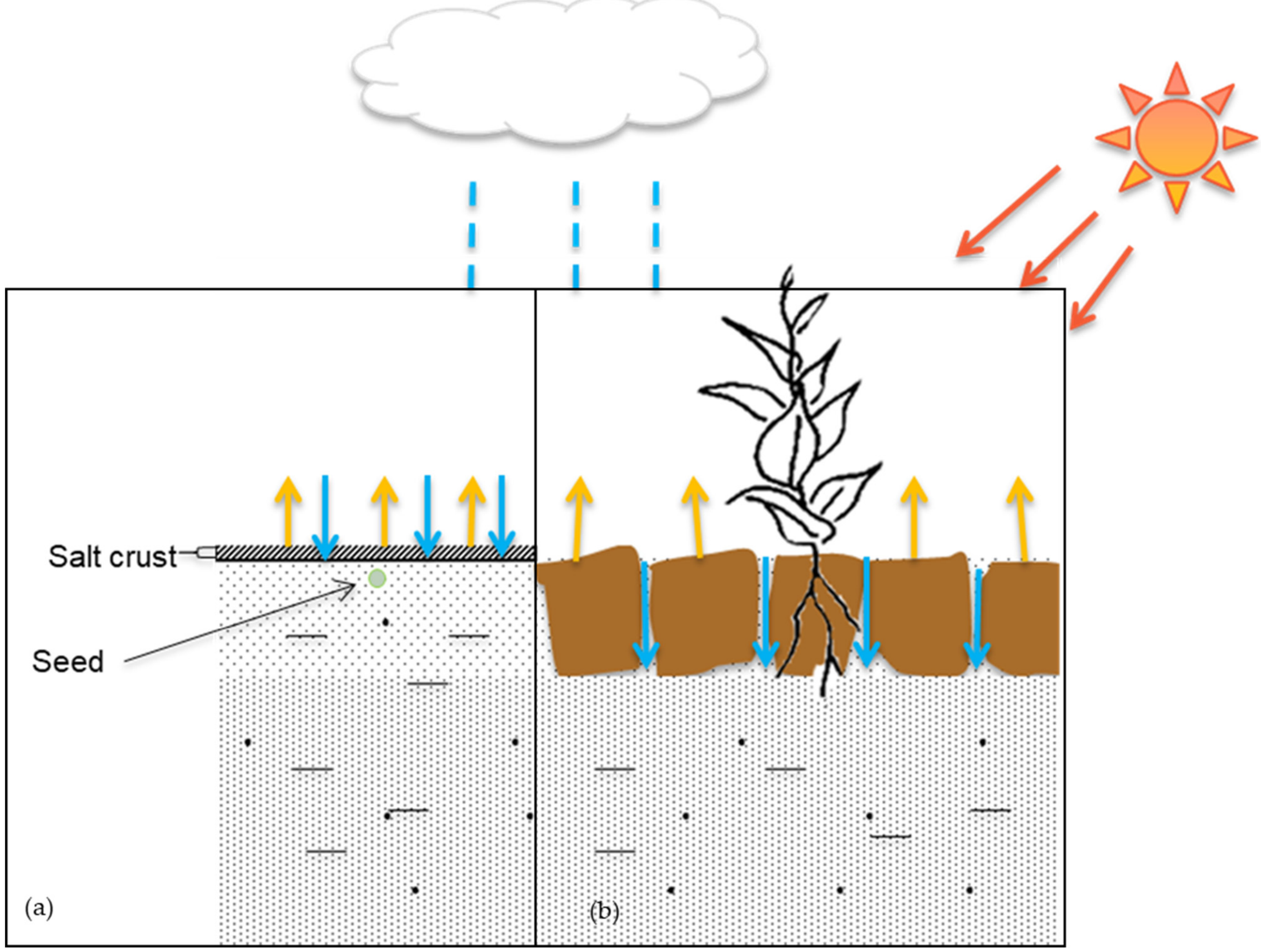

Figure 2. Conceptual model of reclamation of salt-affected area (**a**) before reclamation, (**b**) after reclamation.

3.1. Models as Predictive Tools to Identify Effective Reclamation Practices

The success of a reclamation practice relies on understanding the interaction between plant, soil and climate. Numerical modelling is a meaningful tool to evaluate the interaction of soil, plant and climatic conditions and its effects on the success of reclamation [149]. Field experiments on solute transport are typically based only on simple functional relationships, and cannot entirely cover the spatial and temporal variability at the field scale [63,150,151]. However, numerical models can perform complex scenarios and integrate observed climatic conditions and soil (soil chemical and physical properties as well as soil hydrology) as well as plant factors. Thus, the salt-affected soil reclamation practice/s can be evaluated precisely, and so identified using modelling studies. This also reduces the unnecessary costs associated with examining reclamation methods as well as their implementation through field trials. In particular, modelling can be economically useful for exploring and determining a reclamation technique for land in arid and semi-arid environments with highly variable rainfall patterns, where a period of dry conditions can result in the upward movement of solute to the surface soil and thus restrict plant establishment.

To identify an effective reclamation strategy, a model which can simulate solute transport and compute cation exchange, mineral dissolution, precipitation and changes in soil hydraulic conductivity in relation to the modification of the soil chemistry, as well as the interrelations of all mentioned factors, is required [151–157]. There are several soil hydro-geochemical models that can be used for simulation and projection of solute transport in soil profiles (porous media) and thus the success of reclamation techniques. LEACHM [158], VADOSE/W or SEEP/W [159], UNSATCHEM [160–162] and HYDRUS [153,156] are among these solute transport models. UNSATCHEM and HYDRUS are currently the only models that can consider the effect of soil chemistry on hydraulic conductivity, which is essential for the evaluation of land reclamation strategies [63,154]. Moreover, the major ion chemistry and carbon dioxide modules of UNSATCHEM are included in the HYDRUS package [156], making HYDRUS a more effective tool for assessing reclamation success.

Several studies demonstrated that models can be effective tools for evaluating salt leaching and solute transport in the soil profile [151,163,164] as well as being applied for designing the implementation of amelioration strategies [63,99,149,154,157,165]. For example, studies on the application of a hydro-geochemical model (i.e., HYDRUS) in different climates confirmed that the hydro-geochemical model can accurately predict water and solute transport under different rainfall patterns and evaporation conditions [163,166,167]. Applicability of the hydro-geochemical model was also verified where the physical amendments (plant residue and fine sand) were added to a salt-affected soil profile [63,99,149]. All the above suggests a hydro-geochemical model can be used as a predictive tool for assessing a reclamation approach under natural climatic conditions before upscaling the strategy to field conditions.

3.2. Model Verification to Identify Effective Reclamation Practices

A numerical model needs to be verified before its application to identify effective reclamation strategies. This process includes the calibration and validation of the model. Calibration is defined as a procedure to obtain a set of parameters that provide a statistically satisfying description of the soil system. Validation is the process of examining the accuracy of the model for being representative of the system. The verification procedure is required for any numerical model, even if good performance has already been verified in other studies.

The example of an approach on how to verify and use a soil hydro-geochemical model for finding the best reclamation practice for a saline-sodic soil in semi-arid climates can be found in a series of studies conducted by Shaygan et al. [37,61,63,99,149]. Firstly, Shaygan et al. [61] determined the chemical and physical properties of saline-sodic soil amended with 40% fine sand and 20% woodchips separately (as proposed reclamation strategies to improve porosity and macro-pore volume and thus enhance salt leaching) as well as non-amended soil. Then, a series of column studies were conducted to assess water and solute movement in the amended and non-amended soil profiles [63]. The column studies were used to simulate different rainfall events to amended and non-amended soil profiles [63]. The monitored water flow and solute transport were then used to calibrate the chemical and physical parameters of soil required for HYDRUS modelling [63]. When the soil parameters were calibrated, another series of experiments with a different rainfall series were conducted, followed by statistical analyses to validate the HYDRUS models [63]. Shaygan et al. [99] used the validated HYDRUS models, and applied ten years natural climatic conditions of the study site to evaluate water flow and solute transport (salt leaching) in different profiles. The modelling study for ten years showed that salt leaching is higher in non-amended saline-sodic soil, and the addition of 40% fine sand or 20% woodchips may not be an effective approach for the reclamation of saline-sodic soil to provide improved conditions for revegetation [99]. This study also suggested that a low soil bulk density is sufficient to provide suitable conditions for salt leaching under natural climatic conditions by modifying the pore size distribution [99]. However, the low bulk density or desirable pore system must be sustained. A field study on the saline-sodic soil confirmed the obtained modelling findings, and showed soil ripping to a depth of 15 cm increased the diversity and density of native species' establishment [99]. The series of studies that have been conducted by Shaygan et al. [37,61,63,99,149] suggested that a numerical model can be used as predictive tool to assess the effectiveness of a reclamation strategy by covering complex scenarios and the interaction of soil, plant and climate, both spatially and temporally. Once a validated model has been confirmed and experimentally validated, any scenarios can be simulated by the model to predict the outcome of reclamation strategies. The same modelling approach can be applied to any porous media from non-soil like substrates as can be found in mining such as tailings [168,169] and rocky and gravelly materials [170–172] to evaluate different scenarios on their management strategies.

4. Conclusions

There are several methods to reclaim a salt-affected soil, including salt leaching, the addition of amendments, soil ripping, salt scrapping and revegetation using halophytes. Salt leaching is the most important method among the aforementioned strategies. However, its efficacy depends on soil physico-chemical conditions and climatic conditions of the site. Leaching may result in imbalanced ion content of the soil and thus negatively affect soil conditions. Therefore, on some occasions, a combination of techniques may be required for the reclamation of a salt-affected soil. As an example, a saline-sodic soil may be reclaimed through revegetation using halophytes. However, in arid and semi-arid environments, leaching is a critical factor for successful revegetation, even when salt-tolerant species are used. As rainfall is often the only water source for salt leaching in semi-arid and arid environments, the addition of amendments becomes critical to improve soil physical conditions and hence enhance leaching during rain events, and reduce upward movement of solutes during extended dry conditions. This review paper revealed that identifying a suitable reclamation strategy for a salt-affected land requires understanding the interaction of soil, plant and climate. Therefore, understanding this interaction is recommended before selecting any reclamation techniques. Sustainable and long-term good performance of a reclamation strategy must also be a consideration, as some reclamation techniques are short-term solutions only. The field studies typically used to evaluate the suitability of reclamation practices cannot cover complex spatial and temporal changes involved with the success of reclamation. To close this gap, soil hydro-geochemical numerical models are recommended to be used as decision-making tools to cover complex scenarios, both spatially and temporally, and assist with assessing the effectiveness of a reclamation strategy for salt-affected soils before implementing it. From a future perspective, reclamation of salt-affected land should rely more on modelling techniques to increase the likelihood of reclamation success.

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Appendix A

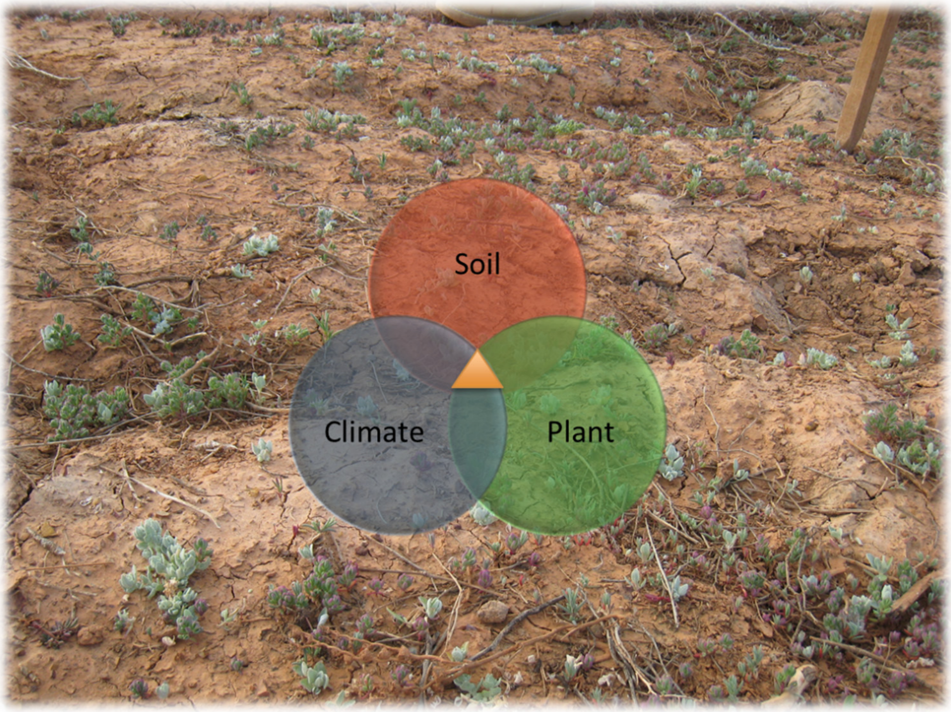

Figure A1. The figure indicating the overlap (small triangle) of soil, plant and climate, which is required knowledge for selection of an effective remediation technique for successful reclamation.

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