

# Review of Sodic Soil Reclamation with a Snapshot of Current Research Activity

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**Abstract:** For centuries, reclamation of sodic soils has been an essential part of cropping practices in several parts of the world. Parallel to increasing population, the need for new cropland constantly re-evaluates land suitability concepts. Therefore, the importance of sodic soils as potential croplands is increasing worldwide. Although theoretically farmers can choose from a wide variety of reclamation options, according to profitability, business plans, and human and financial resources, in practice, few reclamation methods are applied at large scale. This article touches on the early history, 20th Century intensive research, and current trends of sodic soil reclamation. New approaches such as leaching, chemical amendments, addition of organic material, and biological and microbial improvements are discussed, and also brand-new approaches are reviewed. The early history is reviewed using historical books, the achievements of the last hundred years using basic technical literature, mostly books, and the current approaches of our time with fresh publications, mostly papers and two very recent conferences published in English.

**Keywords:** gypsuming; liming; chemical reclamation; new technology; sodic soil

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## 1 Introduction

Our topic, the reclamation of sodic soils (‘Solonetz’ in most soil taxonomies), has already received much attention from researchers. According to Ghassemi et al. (1995), the area of sodic soils in Asia and Australia is approximately 250M ha, more than one third of that in Europe, one fifth in Latin America, one eighth in Africa, and approximately one twentieth in North America and the Near East (comprising the countries of the Arabian Peninsula, Cyprus, Egypt, Iraq, Iran, Israel, Jordan, Lebanon, Palestinian territories, Syria, and Turkey). Fig. 1 shows the worldwide distribution of these soils according to the United Nations Food and Agriculture Organ-

ization database ([www.fao.org](http://www.fao.org) accessed in 2009; [https://www.researchgate.net/figure/Global-distribution-of-sodic-soils\\_fig3\\_42765401](https://www.researchgate.net/figure/Global-distribution-of-sodic-soils_fig3_42765401)).

Speaking exclusively about chemical reclamation, it is common knowledge that sodium ions adsorbed on colloid particles must be replaced by soluble Ca (or Fe, Al) ions. This is very simple in theory, but how to ensure that process progresses to a sufficient degree and quickly, remains an open question. The variation of sodic soil reclamation techniques reflects the range of possible replacement methods, the depth variability of sodic soils, and the availability of possible amendments. Dosage calculations are well described by chemical equations and experimental approaches, and the primary

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issue is the source of reclaiming Ca ions. Are they present in the soil as components of a compound, such as  $\text{CaSO}_4$  or  $\text{CaCO}_3$ ? Are they available at the same depth where Na must be replaced by Ca? If yes, their solubility must be increased so that they can get to the specific macroscopic/microscopic locations where the exchange reaction must take place. Mobilization of Ca from coexisting minerals in the soil might be enhanced by the provision of water and acidification, so that compounds such as  $\text{CaCO}_3$  are dissolved. Typical solution for this is the addition of acidic organic matter, such as barn manure or green manure.

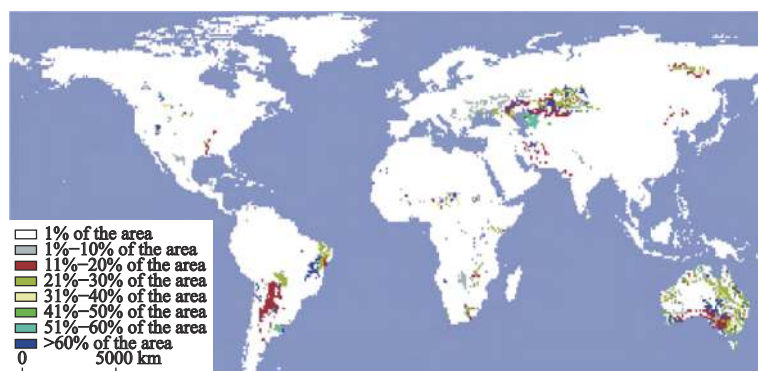
If Ca-containing soil components are available at other depth ranges of the soil profile, the depth distribution must be modified by tillage (e.g., deep plowing) by turning up the deep-lying soil layer to the root zone. If Ca-containing soil components are not available in the soil, then they must be added. The selection of the amendment depends on the chemical properties of the soil that is being reclaimed—mostly the alkalinity/acidity conditions. Another necessary condition may be the speed of reclamation that must be met. Calcium-containing highly soluble salts such as  $\text{CaCl}_2$  (Magdoff and Bresler, 1973) provide fast reclamation, but others such as gypsum dissolve relatively slowly, and lime even slower. Selection of amendments also depends on the availability of cheap materials, such as industrial byproducts.

Amendments must be provided to the sodic layer in order to facilitate dissolution of Ca ions, which requires suitable preparation of the soil by tillage. Distribution of the amendment must be homogeneous, except when sodicity is heterogeneous inside the plot, as it often happens. In this case, amendment dose must follow the spatial variability of the soil sodicity. The amendment must be worked into the topsoil in order to produce its desired effect, ideally after the application of organic matter such as manure. Alternatively, it can be placed on top of the soil or provided in solution, even in brackish ice (Yang et al., 2021; Zhang et al., 2021d). The particle size of solid amendments, such as gypsum/lime powder, has a well-documented effect: the finer the amendment, the faster the speed of reclamation, but applying very fine powder may cause technical difficulties in the field. Leaching with soluble Ca solution that is too fast will not provide full replacement of Na because of decreased contact time (Keren and O'Connor, 1982) with

Na-saturated colloid particles. Na ions displaced from colloids should be leached/drained from soil, otherwise might again dominate the cation exchange locations. Ca is also essential plant nutrient that is taken up by plants, therefore gypsuming/liming must be repeated from time to time.

Dosage and distribution during crop rotation/years and growing seasons have also been studied for several crop rotations (Minhas et al., 2019).

Besides chemical replacement of adsorbed Na, most sodic soils have other issues as well, and sodic soil reclamation is often only one step of full soil improvement, including leveling, leaching, and drainage. In order to link new developments to specific steps of the reclamation process, these steps are listed here. Reclamation starts with the identification of the problem, since not only natural salinization/sodification/alkalinization (Tóth and Kertész, 1996; Jobbágy et al., 2017) or mismanagement of agricultural lands, but also tsunami, hurricane, sea-level rise, and drainage of acid sulfate soils can be the reason for sodification. For example, Gibson et al. (2021) reported that storm surge, sea-level rise, and groundwater pumping can contribute to the salinization and sodification of coastal lands in Southeast USA. Planning the reclamation requires surveying the land to diagnose the severity of sodicity for each location. A recent technological development is the availability of easy, cheap, high-resolution (attribute, spatial, and temporal) and accurate survey methods that can be nonspecific, panchromatic (Tóth et al., 1998), and Normalized Differential Vegetation Index but also specific using a salinity index or using special sensors, such as electromagnetic induction or electrical conductivity measurements (Rhoades et al., 1999) being useful when sodicity and salinity closely correlate. After the full survey, selecting the amendment is the next step, which depends on the availability and price of possible amendments. Calculating the dosage of the amendments is possible with long-available chemical reactions/determinations and formulas, but it can also be performed with numerical simulation software to consider several modifying factors. Application of the amendment might have several specific methods regarding placement, distribution, depth range, and the specific timing for the actual crop rotation and season. Phytoremediation is an old reclamation technique (Mishra et al., 2004; Qadir et al., 2007) that is still widely applied. An alternative method is the



**Fig. 1** Distribution of sodic soils. Legend indicates severity of sodicity by indicating percent of area covered by sodic soil. Each area which is colored has some percent covered by sodic soils. Source: FAO/UNESCO Soil Map of the World ([www.fao.org](http://www.fao.org) accessed in 2009)

adaptation to the sodicity of the soil (Farooq et al., 2013) by choosing the most environmentally friendly land use and crop.

## 2 Historical Background

Because of available space limitation we must skip the description of the rich earlier history of this topic. All the books that are mentioned were written by many selected authors who were eminent among their contemporaries. The first widespread, and still useful, practical summary on sodic soil reclamation was the USDA (United States Department of Agriculture) Handbook 60 ‘Diagnosis and improvement of saline and alkali soils’ (Richards, 1954), which helped in identifying the type of problem, provided threshold values (Electrical Conductivity of water saturation extract [ECe] > 4 dS/m for salinity, Exchangeable Sodium Percentage [ESP] > 15 for sodicity, and Sodium Adsorption Ratio [SAR] > 13), and listed chemical equations of different amendments in different types of soils. By using three classes of soil (i.e., calcareous soil, alkaline soil, and slightly acidic soil), the authors suggested distinct possible amendments, showed their equivalent amounts, and helped to calculate doses in a comprehensive manner. During the following decades, there was vivid reclamation activity, which was reflected in many publications; some of these are very notable, such as ‘European Solonetz Soils and Their Reclamation’ edited by Szabolcs (1971), which systematically described soil types, properties, distribution, reclamation techniques, and efficiency in seven countries. Also, ‘Irrigation, Drainage and Salinity’ by Kovda et al. (1973) provided a very

wide international picture and specific suggestions to prevent irrigation-induced salinization. In their book, Sumner and Naidu (1998) focused exclusively on sodic soils, as the title of the book suggests, and covered all theoretical and practical aspects of the same. A milestone of this publication was the suggestion to change the so-far unquestionable threshold value of ESP 15 for sodicity in favor of ESP 6. In the mentioned book of Sumner and Naidu (1998), Rengasamy introduced the concept of dispersive potential, which served as the foundation of a new concept. A special feature of the book was the description of full management case studies from all over the world, with six countries detailed. There were two editions of the book ‘Agricultural Salinity Assessment and Management’ (Wallender and Tanji, 2011), which was intended to replace Handbook 60 with up-to-date methods and much larger coverage, such as detailing reclamation without amendment, the relationship between infiltration velocity and gypsum reclamation, and the effect of gypsum fineness. By this time, the general utilization of the Quirk and Schofield (1955) diagram, which shows the combined effect of sodicity and salinity on infiltration, became the standard. This and similar diagrams led to the concept of the infiltration threshold, which questioned the validity of a single value of sodicity (as suggested earlier by Richards in 1954) and proved that not one, but several factors affect clay dispersion in sodic soils (Suarez et al., 1984).

## 3 Current Trends

A few publications are surveyed in this section, and relevant data of the selected papers are shown in Table 1,

**Table 1** Main features of some recent studies on the application of amendments/techniques used to reclaim sodic soils

Soil salinity/sodicity and textural class; Experimental conditions; Presence of crops	Amendment	Starting (s)/Control (c) and final (f) soil ESP/SAR	Doses of amendments/(t/ha)	Duration of experiment	Comments	Country	Reference
Saline-sodic irrigated small field plots Siltloam soil with <i>Cynodon dactylon</i> /C. <i>gayana</i>	G	ESPs 57 ESPf 9	2.5	131 d	Effect of grasses X gypsum on infiltration was the main topic	Ethiopia	Abate et al., 2021
Saline-sodic soil in pot experiment with two <i>C. quinoa</i> varieties, Siltloam	G	ESPc 21 ESPf 2.1	47.7	112 d	Effect on quinoa performance was the main topic	Chile	Alcivar et al., 2018
Endosalic Sodic Regosols	Humic substances	ESPs 21 ESPf 3.7	5	112 d			
	Biochar	ESPs 21 ESPf 4.5	22	112 d			
Nonsaline sandy loam in lysimeter with rice/wheat irrigated with saline/sodic water	G, sulfuric acid	ESPs 5.5 ESPf w/o G 31 ESPf w/ G 18.4	For neutralizing RSC	20 yr	Soil structure and water movement were the main topics	India	Minhas et al., 2021
Flue gas desulfurization gypsum Field experiment on various soils	G	Control=irrigated with nonsaline/nonsodic water 60% improvement	0.3 to 60	Various	59 sites were studied	China	Wang et al., 2021a
Saline-sodic soil in field experiment Clay soil with alfalfa	G	ESPs 36 ESPf 8	180 yearly	4 yr	Flue gas desulfurization gypsum	China	Ying et al., 2021
Saline-sodic soil in field experiment Silt soil with wild halophyte plants	G	ESPs 42 ESPf 15	10.9	25 w	Leaching was the main focus	Jordan	Batareseh, 2017
Saline-sodic soil in field experiment Sandy clay loam soil with rice/wheat	G	SARc 280 SARf 20	11	2 yr	Leaching experiment	Pakistan	Murtaza et al., 2009
Sodic loam soil in field experiment Leptic Natrudolls on hayfield	G	SARs 5.39 SARf 1.5	9.1	4 m	Microbiological indication of reclamation in drainage experiment was the main focus	US	Dose et al., 2015
Saline-sodic soil in pot experiment Barley was grown	Voltage was generated	Soluble sodium decreased by 82%	None	61 d	Plant microbial desalination cell was tested	China	Han et al., 2021
Saline-sodic soil extract in test-tube Salt tolerant <i>Bacillus subtilis</i> culture	Bacterium fermentation product	Soluble Na decreased by 28%	None	4 h	Ca-P compound precipitation was inhibited	China	Wang et al., 2021b
Saline-sodic soil in field experiment Clay soil with wheat	G	ESPs 19 ESPf 20	17	2 yr	Tillage was also tested	Egypt	Ding et al., 2021
	Sulfuric acid	ESPs 19 ESPf 14	4.3	2 yr			
	Vermicompost	ESPs 19 ESPf 15	10	2 yr			
Saline-sodic soil in pot experiment Clay loam soil with oat	Vinegar residue +S-K fertilizer	ESPs 75 ESPf 45	1.3	2 m	Nonsodic saline soil was also tested	China	Fan et al., 2018

Notes: G, gypsum; RSC, Residual Sodium Carbonate; ESP, exchangeable sodiumpercentage; SAR, Sodium Adsorption Ratio; h, hour; d, day; w, week; m, month; yr, year

which show that many alternative amendments/techniques exist for the reclamation of sodic soils, though gypsum is still the dominant reclamation material. Doses of amendments and speed of reclamation vary widely depending on experimental conditions—most importantly the sodicity level. Some biological methods of reclamation have recently gained popularity. Jesus et al. (2015) suggested to combine phytoremediation with reclamation, which is an old approach. Kumar et al. (2021) reported that *Prosopis* legume trees improve soil conditions in the following salinity reduction order: *P. juliflora* (64.5%) > *P. chilensis* (61.5%) > *P. articulata* (59.8%); and the increase of carbon stock showed the following order: *P. alba* > *P. juliflora* > others. Abate et al. (2021) reported that grass planting combined with gypsuming improved soil properties, and *Cynodon dactylon* and *Chloris gayana* have an ameliorative effect on infiltration and soil salinity/sodicity/alkalinity that is comparable to small gypsum doses.

Among chemical methods for reclamation, gypsuming and the application of organic matter remain the most popular. Aleívar et al. (2018) studied the effect of these amendments and found that the combination of biochar, humic substances, and gypsum had superior effect on soil and both quinoa genotypes. Minhas et al. (2021) evaluated a 20-year-old reclamation experiment in which soils were irrigated with alkali water and found that watering with high-Residual Sodium Carbonate water decreased soil water storage capacity compared to good-quality water, whereas gypsum and sulfuric acid increased soil water storage capacity; nevertheless, the effect on post-infiltration water storage did not reach below the depth of 30 cm. Wang et al. (2021a) reported the reclamation of sodic soils with flue gas desulfurization gypsum (FGDG). A meta-analysis of 59 locations showed that FGDG had several positive effects on soil and plants, although heavy metal concentration increased in the soil. Ying et al. (2021) described the effect of flue gas desulfurization steel slag on sodic soil properties, where 180 t/ha was applied in each of three consecutive years. Increasing duration improved the reclamation effect, and the effect on physical and chemical soil properties was rapid, but the treatment resulted in salt accumulation at a greater soil depth.

Leaching studies continue to be widespread. Callaghan et al. (2017) reported that although approximately 30% of salts could be leached during the first year of the ex-

periment, water-table rise limited leaching in the second year in clay soil. Batarseh (2017) studied the leaching of calcareous saline-sodic soils in Jordan. All three treatments—gypsum, fresh water (1 dS/m), and saline water (8 dS/m)—reduced salinity, but application of gypsum hastened leaching to twice the original velocity. Murtaza et al. (2009) studied the effects of combinations of irrigation water quality, amendment, and crop rotation on soil properties and economic benefits in saline-sodic soil. According to the results, gypsum/manure and 1st saline-sodic water + 2nd fresh water irrigation provided optimal yield/economic benefit in rice/wheat rotation. On the other hand, soil physical properties were best improved with gypsum, but chemical properties with manure. In order to account for the dispersing effect of rainwater, according to Suarez (2013), more gypsum must be applied regularly when irrigating with saline/sodic water in California. Shafiefar et al. (2021) used HYDRUS-1D for leaching estimation. An inverse method was used to estimate the desalination curve, which was compared to measured data. The results showed that leaching with or without sulfuric acid did not show significant differences in a calcareous gypsiferous saline-sodic soil; moreover, earlier and shallower changes were better estimated than later and deeper ones. Zhurba et al. (2019) suggested specific practical steps for reclaiming/leaching saline-sodic soils in rice cultivation, including technical guidelines for applying sulfuric acid depending on lime/gypsum/soil organic matter/texture/pH conditions in the soil. As a contrast, not amendments, but loosening provided best leaching effect in the study of Shaygan et al. (2018).

Organic matter has long been used as an amendment and is still widely applied today. Ding et al. (2021) combined tillage with vermicompost on an irrigated saline-sodic wheat field in Egypt over two years. They found that the vermicompost had a better effect than gypsum or sulfuric acid, and deep tillage improved the effect of amendments on soil properties and yield. Elkhilifi et al. (2021) used phosphate-lanthanum coated sewage sludge biochar in ryegrass cultivation and found that it provided a large amount of phosphorus and decreased the  $\text{CaCO}_3$  content due to a decomposition reaction. Fan et al. (2018) reported the effect of vinegar residue combined with Si-K fertilizer on saline and saline-sodic soil. They found that vinegar residue reduced the sodicity of saline and saline-sodic soils. Increasing the dose of Si-K

fertilizer further decreased sodicity but increased EC and pH.

The reclamation of sodic soils with microbial products is a very recent development. Han et al. (2021) developed a plant microbial desalination cell and also a soil microbial desalination cell based on the processes of ion migration, plant absorption, bioremediation, and microbial activity. They showed that the plant microbial desalination cell produced a larger effect than the soil microbial desalination cell. Li et al. (2019) published a review on the effect of *Cyanobacteria* for reclaiming salt-affected soils and stated that, in pot cultures, positive effects were found in the few studies so far. Wang et al. (2021b) studied *Bacillus subtilis* broth and found that it provided active phosphate for plants; furthermore, the fermentation liquid suppressed phosphate crystallization and also reduced the pH value, but it increased EC. Dose et al. (2015) studied the functional gene and enzyme activity indicators of sodic soil reclamation by using successional vector trajectories. They found that number of ammonia-oxidizing bacterial gene copies was higher where cropland was amended with gypsum, and that indicators were sensitive to cropping and amendments but not to drainage installation. Xu et al. (2021) studied the composition of bacterial communities in salinity/sodicity gradients in a study carried out at Da'an station (Jilin Province, China) and found large differences between topsoil and 80–100 cm depth layers. Both salinity and sodicity were strong factors determining the bacterial composition.

There are other miscellaneous techniques used in the reclamation of saline and sodic soils, such as the use of  $\text{Fe}_4[\text{Fe}(\text{CN})_6]_3$  for fixing NaCl. In one study, when iron (III) ferrocyanide, a crystallization inhibitor, was added to saline soils, 29%–57% of NaCl was removed after 7 d (Daigh et al., 2016). In another study, after two weeks of iron (III) ferrocyanide application, the amount of salt crystals deposited on the soil surface increased with increasing application rate (Angin et al., 2019).

During their study of the effect of frost, Li et al. (2021a) found that frost heaving improved soil structure in the Yellow River Delta. Rather than particle size distribution, dense arrangement caused unfavorable soil physical properties. They found that the freezing of moister (10%–25% moisture) soil improved structure more. Al-Busaidi et al. (2013) used anionic polyacrylamide and/or gypsum for protecting sodic soils from

erosion successfully.

#### 4 Research in 2021 as Reflected by Two International Conferences

Finally, we browse the relevant papers of two global conferences, which show good representation of two countries that are most affected by salinity. The First IUSS(The International Union of Soil Sciences) Conference on Sodic Soil Reclamation on July 30, 2021 recruited most of its speakers from China, and the Global Symposium on Salt-affected Soils between 20–22 October 2021 aroused great interest among Indian researchers among other nationals. Thus, these two conferences reflect the activity in East and South Asia very well.

The conference on sodic soil reclamation was organized in Changchun, China (Wang and Tóth, 2021) and the following paragraph summarizes its most important findings. Gypsuming was a very popular topic, with the focus being on different gypsum-containing byproducts, dosage, and also combination with other amendments (Zhao et al., 2020). James Oster (2021) described the history of gypsuming and research culminating in the introduction of the cation ratio of soil structural stability (CROSS) index, which was designed to replace the old SAR value. Pichu Rengasamy (2021) described the dispersive and flocculating charge and the weighting factors of common adsorbed cations in sodic soils. Stephen Grattan (Grattan, 2021) described the move from SAR to CROSS and pointed out that there are other factors not yet quantified with similar indexes, such as 'soil texture, dissolved organic carbon, clay composition, pH, calcite, and Al and Fe oxide content.' Ed Barrett-Lennard (Barrett-Lennard, 2021) showed that the salinity of sodic soils might create problems for barley, and using a small amount of gypsum and water retention could provide leaching and consequently increased yield with reclamation. Thomas (2021) described the remediation of secondary sodic soils. Li et al. (2021b) described the effect of different methods. Zhang et al. (2021a) described the effect of amendment application rates on sodic soil reclamation. Aluminum sulfate was suggested by Liu et al. (2021a). A general landscape-scale management was suggested by Liu et al. (2021b), and Liu et al. (2021c) focused on reclamation in dryland agriculture. Jin and Shao (2021) described the benefits of applying biochar, and Zhang et al. (2021b) sug-

gested combining organic amendments with gypsum. Use of brackish ice was suggested by Zhang et al. (2021c; d, e). Phytoremediation of sodic soils was discussed in the presentations of Manzoor (2021) and Saqib et al. (2021).

During the FAO Global Symposium on Salt-affected Soils, the most important development was the presentation of the brand new Global Map of Salt-affected Soils (FAO, 2021), which shows information from 118 countries in 257 419 locations and therefore presents a unique database. There are some shortcomings though, such as the large number of countries without information, such as China, Egypt, Iran, Australia, Kazakhstan, and Mongolia, and hopefully the mentioned countries will prepare their maps soon. There are some new thresholds used that are not easy to fit into existing concepts. The map has the traditional threshold value for sodicity, starting with ESP 15 (Richards, 1954), but recently several studies suggested a much-lower threshold value of ESP 6 (Sumner and Naidu, 1998, Van Orshoven et al., 2014), and this range is not shown on the map. On the other hand, the salinity threshold values are very strict, with two new threshold values below the traditional 4 dS/m (Richards, 1954): 2 and 0.75. A pH of 8.2, as a new threshold, is more strict than the usual 8.5 (Richards, 1954). Using the low EC<sub>e</sub> values, for example, large parts of Ireland and Britain seem to be saline, which is evidently a misinterpretation. With the new thresholds of EC<sub>e</sub> = 2, pH = 8.2, and ESP = 15, the area of saline topsoil is six times larger than the area of sodic topsoils (0–30 cm) and two times larger than that of subsoils (30–100 cm), much distorting the previous 1:1 ratio of saline to sodic soils with threshold values of EC<sub>e</sub> = 4 and ESP = 15, as reported by Ghassemi et al. (1995). Another issue is that since the spatial databases were prepared by national experts and based on independent national approaches, the administrative boundaries are often recognizable. Therefore, the compiled global database needs harmonization across national databases in order to be fully useful across boundaries.

During the mentioned symposium, new issues of sodicity research with a special focus on reclamation were put forth. Melo et al. (2021) described the distribution of sodic soils in Brazilian Amazonia, and Da Martins et al. (2021) also reported sodic soil occurrence in the tropical Brazilian state of Maranhão. Apcarian et al. (2021) reported that sodification accompanies salt accu-

mulation in irrigated areas in Argentina. Paul et al. (2021) reported the significance of palygorskite mineral in sodification in semiarid tropical India.

Bhardwaj et al. (2021) compared three nutrient management systems in improving the nutrient regime of sodic soils and found that with integrated management, the dosage of inorganic fertilizers can be reduced by half, and sodification can be halted. Rai et al. (2021) demonstrated phosphorus fixation after gypsum application in sodic soil.

Ballesterio et al. (2021) compared the efficiency of two agricultural gypsums for the reclamation of sodic soil in Uruguay. Sundha et al. (2021) reported a better effect with flue gas desulfurization gypsum than with mined gypsum in a sodic rice field. Foronda and Flores (2021) and Ahmad et al. (2021) argued that Residual Sodium Carbonate value of irrigation waters is very important characteristic, surpassing SAR in importance for sodicity.

Foronda and Flores (2021) showed that sulfur is more efficient to reduce alkalinity, but gypsum performed better in reducing the sodicity and salinity of the soil. Garelo et al. (2021) demonstrated that from the one-meter maximum water adsorption depth of maize, every ESP value increase caused a 2-cm decrease, resulting in 70 cm available depth at ESP25. Balasubramaniam et al. (2021) bred sorghum varieties suitable for growing in soil sodicity levels reaching ESP32.

## 5 Conclusions

The basic theory of sodic soil reclamation based on colloid-chemical theory and experience is still valid. Theoretical considerations have their foundation in the specific features of sodium ions and salts, such as solubility, valence, and interaction with clay particles, which can be controlled in laboratory conditions. In contrast, it is still not possible theoretically to predict soil properties in a heterogeneous soil profile due to several distinct pedological features, which vary from place to place. Therefore, detailed lateral and depth information of plots is required for the approximate simulation of reclamation processes.

The current technical methods of sodic soil reclamation follow the innovations of our times, such as advanced microelectronic developments, data management, and calculation capacities. The most evident in-

novation that was realized is the advancement of spatially and temporally detailed characterization of the sodicity status of agricultural fields, which is provided by remote and proximal sensing as well as laboratory instrumentation. Other possibilities might be the use of field sensors and automatization, but these are not yet fully utilized due to the still-high costs, but with decreasing cost of instrumentation and the rise of agricultural commodity prices, they certainly will be utilized.

In conclusion, there are general suggestions for the reclamation of sodic soils, but every reclamation must be fitted to the particular land use, preferred crop, spatio-temporal distribution of soil properties, and available amendments. Reclamation of saline and sodic soils remains a very popular topic of investigation in the 21st century, and every new relevant discovery will find its way into the discussion. There are several new ideas, but mostly old techniques prevail in our times. The old techniques are modernized, tested by preliminary simulation, digital processed, or are combined with new ones.

## References

- Abate S, Belayneh M, Ahmed F, 2021. Reclamation and amelioration of saline-sodic soil using gypsum and halophytic grasses: Case of Golina-Addisalem irrigation scheme, Raya Kobo Valley, Ethiopia. *Cogent Food & Agriculture*, 7(1): 1859847. doi: [10.1080/23311932.2020.1859847](https://doi.org/10.1080/23311932.2020.1859847)
- Ahmad W, Zia M H, Shahid S A et al., 2021. In arid and semi-arid environments, restoration of salt-affected soils is a function of soil profile diagnosis and the residual sodium carbonate of irrigation water. *Global Symposium on Salt-affected Soils*. Available at: [https://www.fao.org/fileadmin/user\\_upload/GSP/GSAS21/062.pdf](https://www.fao.org/fileadmin/user_upload/GSP/GSAS21/062.pdf). Cited 20–22 October 2021
- Al-Busaidi A, Yamamoto T, Shimura Y et al., 2013. Controlling sodic soil erosion by electrolytes and polyacrylamide application. In: Shahid S A, Abdelfattah M A, Taha F K (eds). *Developments in Soil Salinity Assessment and Reclamation*, Dordrecht: Springer, 335–348. doi: [10.1007/978-94-007-5684-7\\_22](https://doi.org/10.1007/978-94-007-5684-7_22)
- Alcivar M, Zurita-Silva A, Sandoval M et al., 2018. Reclamation of saline-sodic soils with combined amendments: impact on quinoa performance and biological soil quality. *Sustainability*, 10(9): 3083. doi: [10.3390/su10093083](https://doi.org/10.3390/su10093083)
- Angin I, Sari S, Aksakal E L et al., 2019. The use of iron (III) ferrocyanide soil amendment for removing salt from the soil surface. *Arid Land Research and Management*, 33(1): 91–96. doi: [10.1080/15324982.2018.1474400](https://doi.org/10.1080/15324982.2018.1474400)
- Apcarian A, Imbellone P A, Salaberry J M, 2021. Salinization and sodification in irrigated agricultural areas in arid regions, Northern Patagonia Argentina. *Global Symposium on Salt-affected Soils*. Available at: [https://www.fao.org/fileadmin/user\\_upload/GSP/GSAS21/004.pdf](https://www.fao.org/fileadmin/user_upload/GSP/GSAS21/004.pdf). Cited 20–22 October 2021.
- Balasubramaniam P, Alagesan A, Masilamani P et al., 2021. Evaluation of Sorghum (*Sorghum bicolor* L.) varieties for their tolerance to sodicity level for sustained productivity in salt affected soils. *Global Symposium on Salt-affected Soils*. Available at: [https://www.fao.org/fileadmin/user\\_upload/GSP/GSAS21/047.pdf](https://www.fao.org/fileadmin/user_upload/GSP/GSAS21/047.pdf). Cited 20–22 October 2021.
- Ballester J, Del Pino A, Barbazán M M, 2021. Agricultural gypsum application in soils with of sodium: study in microlysimeter. *Global Symposium on Salt-affected Soils*. Available at: [https://www.fao.org/fileadmin/user\\_upload/GSP/GSAS21/037.pdf](https://www.fao.org/fileadmin/user_upload/GSP/GSAS21/037.pdf). Cited 20–22 October 2021.
- Barrett-Lennard, 2021. Is the adverse effect of sodicity on crop growth mediated by salinity in semi-arid rainfed environments? In: Wang Z, Tóth T (eds). *First IUSS Conference on Sodic Soil Reclamation*. Changchun, China. Book of Abstracts, 15.
- Batarseh M, 2017. Sustainable management of calcareous saline-sodic soil in arid environments: the leaching process in the Jordan valley. *Applied and Environmental Soil Science*, 2017: 1092838. doi: [10.1155/2017/1092838](https://doi.org/10.1155/2017/1092838)
- Bhardwaj A K, Narjary B, Chandra P, 2021. Integrated management of nutrients from organic and inorganic sources increase productivity, soil health and climate resilience of sodic soils. *Global Symposium on Salt-affected Soils*. Available at: [https://www.fao.org/fileadmin/user\\_upload/GSP/GSAS21/032.pdf](https://www.fao.org/fileadmin/user_upload/GSP/GSAS21/032.pdf). Cited 20–22 October 2021
- Callaghan M V, Head F A, Cey E E et al., 2017. Salt leaching in fine-grained, macroporous soil: negative effects of excessive matrix saturation. *Agricultural Water Management*, 181: 73–84. doi: [10.1016/j.agwat.2016.11.025](https://doi.org/10.1016/j.agwat.2016.11.025)
- Da Martins A L S, Teixeira W G, Silva M B E, 2021. Saline soils in the baixada maranhense: a case study in Maranhão state, Brazil. *Global Symposium on Salt-affected Soils*. Available at: [https://www.fao.org/fileadmin/user\\_upload/GSP/GSAS21/002.pdf](https://www.fao.org/fileadmin/user_upload/GSP/GSAS21/002.pdf). Cited 20–22 October 2021.
- Daigh A L M, Klaustermeier A W, 2016. Approaching brine spill remediation from the surface: a new in situ method. *Agricultural & Environmental Letters*, 1(1): 150013. doi: [10.2134/aer2015.12.0013](https://doi.org/10.2134/aer2015.12.0013)
- Ding Z L, Kheir A M S, Ali O A M et al., 2021. A vermicompost and deep tillage system to improve saline-sodic soil quality and wheat productivity. *Journal of Environmental Management*, 277: 111388. doi: [10.1016/j.jenvman.2020.111388](https://doi.org/10.1016/j.jenvman.2020.111388)
- Dose H L, Fortuna A M, Cihacek L J et al., 2015. Biological indicators provide short term soil health assessment during sodic soil reclamation. *Ecological Indicators*, 58: 244–253. doi: [10.1016/j.ecolind.2015.05.059](https://doi.org/10.1016/j.ecolind.2015.05.059)
- Elkhlifi Z, Kamran M, Maqbool A et al., 2021. Phosphate-lanthanum coated sewage sludge biochar improved the soil properties and growth of ryegrass in an alkaline soil. *Ecotoxicology and Environmental Safety*, 216: 112173. doi: [10.1016/j.ecotoxicology.2021.112173](https://doi.org/10.1016/j.ecotoxicology.2021.112173)

- ecoenv.2021.112173
- Fan Y, Shen W Y, Cheng F Q, 2018. Reclamation of two saline-sodic soils by the combined use of vinegar residue and silicon-potash fertiliser. *Soil Research*, 56(8): 801–809. doi: 10.1071/SR18074
- FAO, 2021. Global map of salt-affected soils. Available at: <https://www.fao.org/3/cb7247en/cb7247en.pdf>.
- Farooq S, Akram M, Afzal M et al., 2013. Practical, productive, and environment-friendly utilization of different categories of salt-affected soils in arid and semiarid regions of Pakistan. In: Shahid S A, Abdelfattah M A, Taha F K (eds). *Developments in Soil Salinity Assessment and Reclamation*, Dordrecht: Springer, 349–356. doi: 10.1007/978-94-007-5684-7\_23
- Foronda D A, Flores J L M, 2021. Reclamation of a saline-sodic soil with gypsum and sulphur. *Global Symposium on Salt-affected Soils*. Available at : [https://www.fao.org/fileadmin/user\\_upload/GSP/GSAS21/035.pdf](https://www.fao.org/fileadmin/user_upload/GSP/GSAS21/035.pdf). Cited 20–22 October 2021
- Garello F J, Melani E M, Ploschuk E L et al., 2021. Crop production in sodic soils: Can the corn take the water of the Btn horizon? *Global Symposium on Salt-affected Soils*. Available at : [https://www.fao.org/fileadmin/user\\_upload/GSP/GSAS21/043.pdf](https://www.fao.org/fileadmin/user_upload/GSP/GSAS21/043.pdf). Cited 20–22 October 2021
- Ghassemi F, Jakeman A J, Nix H A, 1995. *Salinization of Land and Water Resources: Human Causes, Extent, Management and Case Studies*. Sydney: University of New South Wales Press Ltd.
- Gibson N, McNulty S, Miller C et al., 2021. *Identification, Mitigation, and Adaptation to Salinization on Working Lands in the U. S. Southeast*. Asheville, NC: U. S. Department of Agriculture Forest Service, Southern Research Station, 69. doi: 10.2737/SRS-GTR-259.
- Grattan S R, 2021. Sodicty and the soil-plant system: Current assessment. In: Wang Z, Tóth T (eds). *First IUSS Conference on Sodic Soil Reclamation*. Changchun, China, Book of Abstracts, 22–24.
- Han X Y, Qu Y P, Li D et al., 2021. Remediation of saline-sodic soil by plant microbial desalination cell. *Chemosphere*, 277: 130275. doi: 10.1016/j.chemosphere.2021.130275
- Jesus J M, Danko A S, Fiúza A et al., 2015. Phytoremediation of salt-affected soils: a review of processes, applicability, and the impact of climate change. *Environmental Science and Pollution Research*, 22(9): 6511–6525. doi: 10.1007/s11356-015-4205-4
- Jin F, Shao X W, 2021. Biochar application improves soil nutrient content, soil enzyme activity, cell membrane permeability, rice grain yield and quality in saline-sodic paddy fields. *First IUSS Conference on Sodic Soil Reclamation*. Changchun, China, Book of Abstracts, 25.
- Jobbágy E G, Tóth T, Nosetto M D et al., 2017. On the fundamental causes of high environmental alkalinity (pH ≥ 9): An assessment of its drivers and global distribution. *Land Degradation & Development*, 28, (7): 1973–1981. doi: 10.1002/ldr.2718
- Keren R, O'Connor G A, 1982. Gypsum dissolution and sodic soil reclamation as affected by water flow velocity. *Soil Science Society of America Journal*, 46, (4): 726–732. doi: 10.2136/sssaj1982.03615995004600040012x
- Kovda V A, Van Den Berg C, Hagan R M, 1973. Irrigation, drainage and salinity. In: Box P O (ed.) *An International Source Book, FAO/UNESCO, Hutchinson & Company (Publishers) Ltd., 3 Fitzroy Square, London, England*. New York: UNIPUB, Inc.
- Kumar P, Mishra A K, Chaudhari S K et al., 2021. Different *Prosopis* species influence sodic soil ecology by favouring carbon build-up and reclamation in North-West India. *Tropical Ecology*, 62(1): 71–81. doi: 10.1007/s42965-020-00126-1
- Li H, Zhao Q Y, Huang H, 2019. Current states and challenges of salt-affected soil remediation by cyanobacteria. *Science of the Total Environment*, 669: 258–272. doi: 10.1016/j.scitotenv.2019.03.104
- Li K S, Li Q X, Geng Y H et al., 2021a. An evaluation of the effects of microstructural characteristics and frost heave on the remediation of saline-alkali soils in the Yellow River Delta, China. *Land Degradation & Development*, 32, (3): 1325–1337. doi: 10.1002/ldr.3801
- Li M Z, Zhang W C, Sun Z T et al., 2021b. Influence of different gypsum application methods on the distribution of water and salt in soil profile. In: Wang Z, Tóth T (eds). *First IUSS Conference on Sodic Soil Reclamation*. Changchun, China: Book of Abstracts, 28.
- Liu J H, Wang H B, Hao X M et al., 2021a. Distribution of fluorine in saline sodic soil and the effect of aluminum sulfate on fluorine migration as an amendment in paddy field. In: Wang Z, Tóth T (eds). *First IUSS Conference on Sodic Soil Reclamation*. Changchun, China, Book of Abstracts, 33–35.
- Liu X J, Gu K, Feng X H, 2021b. Innovations in the efficient utilization of saline-alkali land resources. In: Wang Z, Tóth T (eds). *First IUSS Conference on Sodic Soil Reclamation*. Changchun, China, Book of Abstracts, 35–36.
- Liu H T, Sun Y Y, Gao Y S et al., 2021c. Improvement of land productivity in dry farming conditions in the saline-alkali lands of Songnen Plain. In: Wang Z, Tóth T (eds). *First IUSS Conference on Sodic Soil Reclamation*. Changchun, China: Book of Abstracts, 30.
- Magdoff F, Bresler E, 1973. Evaluation of methods for reclaiming sodic soils with CaCl<sub>2</sub>. In: Hadas A, Swartzendruber D, Rijtema P E, et al (eds). *Physical Aspects of Soil Water and Salts in Ecosystems*. Berlin, Heidelberg: Springer, 441–452. doi: 10.1007/978-3-642-65523-4\_44
- Manzoor Q, 2021. Phytoremediation of sodic soils. In: Wang Z, Tóth T (eds). *First IUSS Conference on Sodic Soil Reclamation*. Changchun, China: Book of Abstracts, 40–41.
- Melo V F, De Matos C H L, Do Vale Júnior J F, 2021. Distribution of sodium-affected soils in the Amazon: genesis, Characterization and agricultural aptitude. *Global Symposium on Salt-affected Soils*. Available at: [https://www.fao.org/fileadmin/user\\_upload/GSP/GSAS21/030.pdf](https://www.fao.org/fileadmin/user_upload/GSP/GSAS21/030.pdf). Cited 20–22 October 2021.
- Minhas P S, Qadir M, Yadav R K, 2019. Groundwater irrigation

- induced soil sodification and response options. *Agricultural Water Management*, 215: 74–85. doi: [10.1016/j.agwat.2018.12.030](https://doi.org/10.1016/j.agwat.2018.12.030)
- Minhas P S, Bali A, Bhardwaj A K et al., 2021. Structural stability and hydraulic characteristics of soils irrigated for two decades with waters having residual alkalinity and its neutralization with gypsum and sulfuric acid. *Agricultural Water Management*, 244: 106609. doi: [10.1016/j.agwat.2020.106609](https://doi.org/10.1016/j.agwat.2020.106609)
- Mishra A, Sharma S D, Pandey R, 2004. Amelioration of degraded sodic soil by afforestation. *Arid Land Research and Management*, 18(1): 13–23. doi: [10.1080/15324980490244960](https://doi.org/10.1080/15324980490244960)
- Murtaza G, Ghafoor A, Owens G et al., 2009. Environmental and economic benefits of saline - sodic soil reclamation using low-quality water and soil amendments in conjunction with a rice-wheat cropping system. *Journal of Agronomy and Crop Science*, 195(2): 124–136. doi: [10.1111/j.1439-037X.2008.00350.x](https://doi.org/10.1111/j.1439-037X.2008.00350.x)
- Oster J D, 2021. History of the roles of gypsum in soil reclamation and establishment of SAR/EC water quality guidelines. In: Wang Z, Tóth T (eds). *First IUSS Conference on Sodic Soil Reclamation*. Changchun, China, Book of Abstracts, 38–39.
- Paul, Vasu R D, Karthikeyan K et al., 2021. Minerals (carbonate and palygorskite) induced natural soil degradation (sodicity and poor drainage) in Vertisols of semi-arid Central India. Global Symposium on Salt-affected Soils. [https://www.fao.org/fileadmin/user\\_upload/GSP/GSAS21/023.pdf](https://www.fao.org/fileadmin/user_upload/GSP/GSAS21/023.pdf). Cited 20–22 October 2021.
- Qadir M, Oster J D, Schubert S et al., 2007. Phytoremediation of sodic and saline-sodic soils. *Advances in Agronomy*, 96: 197–247. doi: [10.1016/S0065-2113\(07\)96006-X](https://doi.org/10.1016/S0065-2113(07)96006-X)
- Quirk J P, Schofield R K, 1955. The effect of electrolyte concentration on soil permeability. *Journal of Soil Science*, 6, (2): 163–178. doi: [10.1111/j.1365-2389.1955.tb00841.x](https://doi.org/10.1111/j.1365-2389.1955.tb00841.x)
- Rai A K, Sundha P, Basak N, 2021. Inorganic and organic amendments and irrigation water quality affect P losses in saline-sodic soil. Global Symposium on Salt-affected Soils. [https://www.fao.org/fileadmin/user\\_upload/GSP/GSAS21/034.pdf](https://www.fao.org/fileadmin/user_upload/GSP/GSAS21/034.pdf). Cited 20–22 October 2021.
- Rengasamy, P. 2021. Decisive factors in the reclamation of sodic soils: a reappraisal. In: Wang Z, Tóth T (eds). *First IUSS Conference on Sodic Soil Reclamation*. Changchun, China, Book of Abstracts, 42–45.
- Rhoades J R, Chanduvi F, Lesch S, 1999. *Soil Salinity Assessment. Methods and Interpretation of Electric Conductivity Measurements*. Rome: Food and Agriculture Organization of the United Nations.
- Richards L A, 1954. *Diagnosis and Improvement of Saline Alkali Soils, Agriculture, 160, Handbook 60*. Washington D C: US Department of Agriculture.
- Saqib Z A, Javaid A, Riaz H Q et al., 2021. Management of Eucalyptus camaldulensis plantation for bioenergy production, carbon sequestration and phytoremediation of saline landscapes of Punjab Pakistan. In: Wang Z, Tóth T (eds). *First IUSS Conference on Sodic Soil Reclamation*. Changchun, China, Book of Abstracts, 46–48.
- Shafieifar S, Firouzi A F, Khademalrasoul A, 2021. Estimation of electrical conductivity of saline-sodic soils during leaching process using HYDRUS-1D. *Water and Soil Science*, 31(4): 55–68. doi: [10.22034/WS.2021.12252](https://doi.org/10.22034/WS.2021.12252)
- Shaygan M, Reading L P, Arnold S et al., 2018. The effect of soil physical amendments on reclamation of a saline sodic soil in a semi-arid climatic environment: prediction of the reclamation and revegetation success. *Arid Land Research and Management*. in press
- Suarez D L, Rhoades J D, Lavado R et al., 1984. Effect of pH on saturated hydraulic conductivity and soil dispersion. *Soil Science Society of America Journal*, 48, (1): 50–55. doi: [10.2136/sssaj1984.03615995004800010009x](https://doi.org/10.2136/sssaj1984.03615995004800010009x)
- Suarez D L, 2013. Use of marginal-quality waters for sustainable crop production. In: Shahid S A, Abdelfattah M A, Taha F K (eds). *Developments in Soil Salinity Assessment and Reclamation*. Dordrecht: Springer, 367–381. doi: [10.1007/978-94-007-5684-7\\_25](https://doi.org/10.1007/978-94-007-5684-7_25)
- Sumner M E, Naidu R, 1998. *Sodic Soils: Distribution, Properties, Management, and Environmental Consequences*. New York: Oxford University Press.
- Sundha P, Basak N, Rai A K et al., 2021. Utilization of flue gas desulfurization (FGD) gypsum in reclamation of sodic soil. Global Symposium on Salt-affected Soils. [https://www.fao.org/fileadmin/user\\_upload/GSP/GSAS21/048.pdf](https://www.fao.org/fileadmin/user_upload/GSP/GSAS21/048.pdf). Cited 20–22 October 2021.
- Szabolcs I, 1971. *European Solonetz Soils and Their Reclamation*. Budapest: Akadémiai Kiadó, 1971: 204.
- Thomas D, 2021. Remediation of sodium-rich oilfield produced water-impacted soils. In: Wang Z, Tóth T (eds). *First IUSS Conference on Sodic Soil Reclamation*. Changchun, China, Book of Abstracts, 19.
- Tóth T, Kertész M, 1996. Application of soil-vegetation correlation to optimal resolution mapping of solonchic rangeland. *Arid Soil Research and Rehabilitation*, 10(1): 1–12. doi: [10.1080/15324989609381415](https://doi.org/10.1080/15324989609381415)
- Tóth T, Pásztor L, Kertész M et al., 1998. Allocation of soil reclaiming material based on digital processing of aerial photograph. ISPRS. International Archives of Photogrammetry and Remote Sensing. Commission VII. Symposium. Resource and Environmental Monitoring. 1998: 178–181.
- Van Orshoven J, Terres J M, Tóth T, 2014. *Updated Common Bio-Physical Criteria to Define Natural Constraints for Agriculture in Europe*. Luxembourg: Office for Official Publications of the European Communities, 2012: 75.
- Wallender W W, Tanji K K, 2011. *Agricultural Salinity Assessment and Management*. Reston: American Society of Civil Engineers (ASCE).
- Wang Y G, Wang Z F, Liang F et al., 2021a. Application of flue gas desulfurization gypsum improves multiple functions of saline-sodic soils across China. *Chemosphere*, 277: 130345. doi: [10.1016/J.CHEMOSPHERE.2021.130345](https://doi.org/10.1016/J.CHEMOSPHERE.2021.130345)
- Wang Z C, Tóth T, 2021. *First IUSS Conference on Sodic Soil*

- Reclamation*. Changchun, China: International Union of Soil Sciences.
- Wang Z Y, Tan W J, Yang D Q et al., 2021b. Mitigation of soil salinization and alkalization by bacterium-induced inhibition of evaporation and salt crystallization. *Science of the Total Environment*, 755: 142511. doi: [10.1016/j.scitotenv.2020.142511](https://doi.org/10.1016/j.scitotenv.2020.142511)
- Xu J S, Gao W, Zhao B Z et al., 2021. Bacterial community composition and assembly along a natural sodicity/salinity gradient in surface and subsurface soils. *Applied Soil Ecology*, 157: 103731. doi: [10.1016/j.apsoil.2020.103731](https://doi.org/10.1016/j.apsoil.2020.103731)
- Yang F, Wang Z C, Zhu W D et al., 2021. Long-term effects of combining gypsuming with brackish ice irrigation on soil desalinization and crop growth in abandoned saline-sodic land. *Archives of Agronomy and Soil Science*, 67(14): 2033–2047. doi: [10.1080/03650340.2020.1820487](https://doi.org/10.1080/03650340.2020.1820487)
- Ying Y Q, Lu S G, Shi H X et al., 2021. Flue gas desulfurization (FGD) steel slag ameliorates salinity, sodicity, and adverse physical properties of saline-sodic soil of middle Yellow River, China. *Environmental Science and Pollution Research*, 28(27): 36765–36774. doi: [10.1007/S11356-021-13338-2](https://doi.org/10.1007/S11356-021-13338-2)
- Zhang W X, Zhan W C, Tia R R et al., 2021a. Effect of different amendment application rates on sodic soil reclamation. In: Wang Z, Tóth T (eds). *First IUSS Conference on Sodic Soil Reclamation*. Changchun, China, Book of Abstracts, 75.
- Zhang J, Zhang W C, Sun Z T et al., 2021b. Reclamation effect of gypsum and organic fertilizer on saline-alkali soil in Inner Mongolia. In: Wang Z, Tóth T (eds). *First IUSS Conference on Sodic Soil Reclamation*. Changchun, China: Book of Abstracts, 72–73.
- Zhang L, Yang F, Wang Z C et al., 2021c. Salinity fractionation of saline-sodic soils reclaimed by calcium chloride-amended brackish ice. In: Wang Z, Tóth T (eds). *First IUSS Conference on Sodic Soil Reclamation*. Changchun, China: Book of Abstracts, 74.
- Zhang L, Ge A H, Tóth T et al., 2021d. Soil bacterial microbiota predetermines rice yield in reclaiming saline-sodic soils leached with brackish ice. *Journal of the Science of Food and Agriculture*, 101(15): 6472–6483. doi: [10.1002/jsfa.11319](https://doi.org/10.1002/jsfa.11319)
- Zhang L, Yang F, Wang Z C et al., 2021e. Salinity fractionation of saline-sodic soils reclaimed by CaCl<sub>2</sub>-amended brackish ice. *Arid Land Research and Management*, 36(2): 145–162. doi: [10.1080/15324982.2021.1981488](https://doi.org/10.1080/15324982.2021.1981488)
- Zhao D D, Wang Z C, Yang F et al., 2020. Amendments to saline-sodic soils showed long-term effects on improving growth and yield of rice (*Oryza sativa* L.). *PeerJ*, 8: e8726. doi: [10.7717/peerj.8726](https://doi.org/10.7717/peerj.8726)
- Zhurba V, Chayka Y, Gucheva N et al., 2019. Modern technologies of alkalized and sodic soils reclamation. *E3S Web of Conferences*, 135: 01087. doi: [10.1051/e3sconf/201913501087](https://doi.org/10.1051/e3sconf/201913501087)