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An overview of emerging trends in sodicity reclamation and enhanced food production

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Soil salinity and sodicity have emerged as serious environmental concerns worldwide. The poor soil structure, variability in soil chemical properties and low nutritional status restrict the crop growth with lower productivity in these soils. Around 50 % of the world's arable lands are moderately or highly affected by different levels of degradation. Sodic soils are characterized by high pH and exchangeable sodium percentage, poor hydraulic conductivity with large clay dispersion and significantly low nutrient availability. Gypsum application is the most widely adopted technology for sodic soil reclamation. However, considering the issues related to the availability and purity of mined gypsum, other alternatives are also explored. Some potential industrial by-products, organic sources, and conjunctive synthetic and organic formulations for rapid and cost-effective alternatives to degraded land reclamation are discussed in the article.

Keywords: Crop productivity, Degradation, Nutrients, Reclamation, Soil sodicity

INDIA accounts for 6.73 million hectares of land affected by salinity and sodicity, which impacts the livelihood security in arid and semi-arid regions. Out of this total salt-affected area, sodic soils account for more than 50% (3.77 m ha). The areas are expected to increase under extensive irrigation with RSC and high SAR water. Sodic soils, or alkali soils, contain higher levels of sodium (Na^+) relative to the calcium (Ca^{2+}) and magnesium (Mg^{2+}) in the soil exchange sites and the soil solution. The exchangeable sodium percentage is more than 15, $pH_s > 8.2$ and variable ECe. The soils are characterized by poor physical structure with larger clay dispersion, less pore space and poor hydraulic conductivity. These soils are often low in organic matter and other nutrients. High alkaline hydrolysis, and toxic appearance of Na^+ and the precipitation of Ca^{2+} as $CaCO_3$ further exacerbate the Na-induced toxicity and nutritional deficiency. The widely used chemical ameliorants in saline – sodic soils are gypsum, elemental sulphur, phosphogypsum, FGD gypsum, silicious chalk, etc. Besides, organic sources such as farmyard manure (FYM), press mud, corn stalks, city waste compost, biogas slurry and crop residue are also used with reduced doses of gypsum to amend the salt-affected soils.

Sodic soil in Etah district of Uttar Pradesh

Sodic soil reclamation

Gypsum, chemically $CaSO_4.2H_2O$ is the most effective amendment source in sodic soils. The gypsum requirement (GR) is calculated based on the amount of salts present in the soil and other parameters like soil structure, water quality available for irrigation and crop variety opted. The reaction activity of the gypsum involves the replacement of Na^+ from the exchange complex by Ca^{2+} ions through leaching to the lower depths. Gypsum is made available to farmers through different agencies across the country, like the World Bank, European Union, and State Soil Reclamation and Development Corporations, other developmental agencies etc. It is reported that 2.10 M ha of alkali lands have been reclaimed by different technologies, with the largest area reclaimed in Punjab (0.79 M ha), then Uttar Pradesh (0.73 M ha), followed by Haryana (0.35 M ha) and a total of 0.70 M ha in other states.

Industrial waste by-products are other ameliorants having potential for reclamation of the degraded soils. Fly–ash contains nutrients like silicon (Si), aluminium (Al), iron (Fe), calcium (Ca), magnesium (Mg), sodium (Na), potassium (K), phosphorus (P), and sulfur (S) essential for plant growth. It also contains micro-nutrients such as boron (B), copper (Cu), and zinc (Zn). Biomethanated spentwash (PBSW) is produced during the process methane gas generation from raw spent wash. It contains high organic carbon, calcium and potassium as nutrients for improved plant growth. Sugarcane processing industries produce pressmud with an estimated production of 3 tonnes of pressmud cake from 100 tonnes of crushed sugarcane. Utilization of pressmud in sodic soil amelioration is well reported.

Manures like farm yard manure (FYM) are low-cost, locally available source for application to degraded agricultural lands. It helps increase the amount of water-soluble salts, improves soil nutrients, and increases crop production. It also increases the cation exchange capacity and soluble and exchangeable K, restricting the Na^+ entry into the exchange complex and improving the soil structure, thereby supporting crop growth in sodic environment.

Innovative reclamation sources to combat soil sodicity

Sodic soil requires high Ca^{++} sources for replacing the Na^+ in the soil exchange sites and the soil solution. The mined gypsum with high purity and availability to the farmers is an issue nationwide. ICAR-CSSRI has explored some potential industrial by-products, organic sources, and conjoint synthetic and organic formulations for rapid and cost-effective alternatives to degraded land reclamation.

Flue gas desulfurization gypsum (FGDG), is the by-product of the coal-fired power generation plants produced during scrubbing of sulfur from combustion gases. Applications of FGDG in sodic soils supply Ca^{2+} ions to replace the Na^+ in the soil matrix and improve physico-chemical properties, reduce the nutritional losses and enhance the crop yield; thereby, increasing crop productivity. Co-utilization of FGDs with organic materials (manures, composts, bio-solids) is more beneficial in terms of improving soil physical and chemical properties and supply of essential nutrients. The FGD gypsum having a high purity percentage (>90%), could be a potential source of sodic soil reclamation.

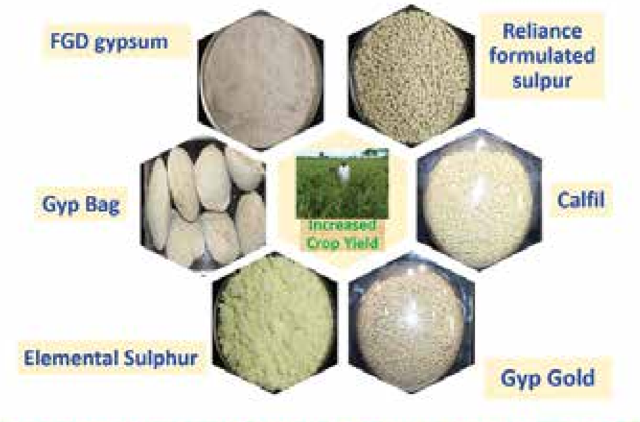
Sulphuric acid (H_2SO_4) application in the calcareous sodic soils reacts with the soil calcium carbonate ($CaCO_3$) and releases calcium sulphate, neutralizing the free sodium carbonate in soils. Sulphuric acid also decreases the alkalinity of irrigation water, but the handling and transportation is an issue.

Elemental S is used to reclaim the calcareous–sodic soil. It is oxidized to H_2SO_4 by the microbial activities (*Thiobacillus thiooxidans*) under moist conditions and converts sodium carbonate and bicarbonate to sodium sulphate. Elemental sulphur-based formulation (Reliance formulated S) application increased 8–225% crop yield in low to highly sodic soils compared to unreclaimed sodic soils. The soil pH was reduced by 0.6–1.5 units with the application of sulphur after the crop harvesting in the first season with the benefit-cost ratio from 1.22 to 1.70 in different agro-ecologies.

Marine gypsum is another by-product produced in the coastal areas of Gujarat and Tamil Nadu during the production of common salt by solar evaporation. Approximately one tonne of salt production produces around 30–50 kg of marine gypsum and is expected to proportionally increase with the increased solar salt production in the nation.

Silicious chalk is the amorphous material recovered from the gypsum mines. It contains silica, calcium and other soil nutrients for sodic soil reclamation. The experiments conducted at farmers' fields have shown an increase in the yield of rice and wheat crops of sodic soils in Haryana and Punjab, and rice crop yield in acidic soils of West Bengal. Further, biological interventions for better nutrient use efficiency of silicious plants are being assessed.

The application of city waste compost (CWC) in the amelioration of high pH sodic soils improves the soil structure and aggregation, increases the



Alternate amendment sources for sodic soil reclamation

Improved crop growth in sodic soil at farmer's field in Nagawan village, Patiala, Punjab hydraulic conductivity and cation exchange capacity. The conjunctive use of the gypsum (25 GR) and CWC decreases the soil *p*H, accelerates the NaCl leaching, decreases the exchangeable sodium percentage, and increases water infiltration. The increase in the soil beneficial organisms tends to reduce the plant pathogens. It is reported that the sole application of gypsum in the sodic soils reduces the nitrogen and phosphorus availability; this can be improved with the CWC application in conjunction with gypsum. The rapid acidulation of the compost and manure with elemental S (S°) and S° oxidisers alleviates the sodicity stress by declining the soil pH within 28 days of soil incubation is an improved alternative to sodic soil reclamation.

The biogas slurry (BGS) is the by-product produced from the biogas plants as an emerging organic source for the nutrient-deficient, degraded sodic soils. BGS is a rich source of organic carbon, nitrogen, phosphorus, potassium and as well as micro elements like Ca, Zn, Mg, S, Fe, Cu, and Mn based on the type of feedstock used during the fermentation. The application of biogas slurry improves the organic content in soil, macro- and micro-nutrients in soil and reduces the N_2O emissions. The conjoint application of slurry (25% N requirement) and sub-optimal doses (75%) of NPK fertilizers has shown higher crop productivity and long-term nutrient sustainability. This fermented organic manure is reported to reduce the load of synthethic fertilizer requirement by 20%. The holistic approach works under the umbrella of government scheme 'GOBARdhan' towards integrated agri–waste management and organic feedstock digestate utilization for environmental stabilization and bio-circular economy, ensuring food safety and sustainable development.

Arbuscular Mycorrhizal Fungi (AMF) enhance the crop resilience under stress conditions, particularly in salt-affected soils (SAS). These fungi establish mutualistic associations with plant roots, forming extensive hyphal networks that significantly improve the uptake of growth-limiting nutrients such as phosphorus and micronutrients. Under salt-stressed environments, where nutrient availability and water absorption are limited, AMF maintain ionic balance by reducing sodium accumulation and promoting potassium uptake in crops, thereby protecting cellular functions. Additionally, they boost the plant's antioxidant defense system and modulate stress-related hormones, which collectively enhance tolerance to salinity. AMF produces organic acids and glomalin, which play a crucial role in chelating heavy metals, boosting carbon sequestration, preventing soil erosion, and stabilizing soil macro-aggregates ultimately contributing to improved soil health. Their mycelial hyphae aid in the formation of soil aggregates, thereby enhancing soil structure. Additionally, AMF also increases phosphorus availability in the soil through the synthesis of phosphatase enzymes. Phosphate-solubilizing bacteria (PSB) complement this process by releasing organic acids, siderophores, gluconic acid, and ketogluconic acid, which facilitate mineralization of organic phosphorus in the soil. Native AMF strains, being well-adapted to local soil and climatic conditions, offer a cost-effective and sustainable strategy for mitigating salt stress, reducing dependency on chemical inputs, and improving overall soil health through better structure and water retention.

SUMMARY

Soil sodicity deleteriously affects the soil health and crop productivity in many of the arid and semi–arid regions of the country and is aggravated with emerging secondary salinization. Gypsum application is one of the methods adopted for sodicity reclamation, but the issues of availability and purity of agricultural-grade gypsum have diverted attention towards the alternative sources. Presently, CSSRI is working on the utilization of elemental sulphur, flue gas desulfurization gypsum (FGDG), marine gypsum, silicious chalk, pressmud CWC, biogas slurry, AMF, etc. for the reclamation of sodic soils with larger stock availability. The farmers' field experiments are being conducted to assess the potential of emerging sources in refurbishing the sodic soils and boosting crop yield.

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