and cost optimization. Actual amount of RFS to be applied needs to be corrected for purity (90%) of RFS.

- Applications of two tonnes ha^{-1} of FYM or crop residue uniformly in one ha land improve the efficiency of the RFS based soil reclamation.
- Applying the RFS pellets preferably in flooded soil followed by light harrowing to ensure the disintegration of swollen pellets and mixing in top 5–7 cm soil depth. If water availability is a problem, apply the RFS in a moist field and irrigate the field after mixing in the top 5–7 cm soil depth.
- Transplant the salt–tolerant rice varieties after 15–20 day of application of the amendment.
- Rice seedlings of 3–4 week age is transplanted in puddled field, ensuring 3 to 4 seedlings per hill and maintaining 15 to 20 cm distance between the hills.
- Follow the alternate wetting and drying condition to ensure oxidation and leaching of the salt produced during reclamation
- Recommended varieties of the wheat or berseem crop should be raised in *rabi* season (Table 4) for better yield during the reclamation process. After 2–3 years, normal crop can be taken without restriction on choice.
- Green manuring of the salt–tolerant *Sesbania* (dhaincha) should be raised during summer to supply organic matter and nitrogen in these soils.
- In first *rabi* cropping season light irrigation should be followed to avoid injury to the plants due to accumulation of salt produced by S°–oxidation during *rabi* season in initial establishment stage.
- Proper nutrient management schedule should be followed to avoid stress because of nutrient stress (Table 5).

Note: Combined application of RFS and 15–25% gypsum gives a better response; inoculation of microbial consortia with farmyard manure or crop residue also enhances the efficiency of reclamation by 15–20% in different soil types.

Table 4. Sodicity–tolerant cultivars

Crop	Cultivars
Paddy	CSR30, CSR36, CSR56, CSR60 and CSR76
Wheat	KRL210, KRL213 and KRL283
Indian mustard	CS56, CS58, CS60, CS61 and CS62
Gram	Karnal Chana–1
Lentil	PDL-1 and PSL-9
Dhaincha	CSD 123 and CSD 137

Table 5. Nutrient management schedule during/post reclamation of sodic soils

Nutrient	Dose	Schedule	Remark
Nitrogen	125% of the recommended dose during the initial 3–4 years	Split application 1/3rd each at sowing, 21 and 45 days after sowing	To compensate for low SOC and biological activity
Phosphorus	No P fertilizer needed for the initial 3–4 years	---------	High Olsen–P in sodic soils, avoid eutrophication and wasteful expenditure
Zinc	25–40 kg zinc sulphate initial 3-–4 years	Soil application at sowing time	Later–stage soil test–based application recommended

#application of 10.0 Mg ha^{-1} of farmyard manure or city waste compost improves the efficacy of the amendment

Reclamation cost

Cost of the reclamation depends upon the quantity and quality of the amendment required to reclaim the soil. Quantity of the amendment needed also depend upon the ESP of the soil, depth of reclamation and alkali tolerance of the crop. The capital invest for sodic soil reclamation using RFS (90% purity) had been worked out to be ₹ 70000 per ha (considering the RFS cost at ₹ 14.0 kg^{-1}). The RFS is 6.5 times less bulky compared to mineral gypsum therefore on equivalent basis amendment needed and field application charges will be 5–6 times less than the mineral gypsum. Besides, RFS based protocol don't need 7–8 days continuous ponding of water for leaching of salt in contrast to mineral gypsum based reclamation.

Economic feasibility

The economic feasibility analysis assuming 12% opportunity cost of the capital revealed that the benefit cost ratio varied from 1.22 to 1.70 in different agroecologies. The payback period was in the range of 2–3 years.

Specific advantage over the gypsum technology

(I) Consistent quality of the amendment with guarantee of minimum purity.

(ii) Reduced cost of transportation because of about 6.5 times less bulky compared to 70% pure mineral gypsum.

(iii) Free flowing material saved 70–80% energy, labour and time required for amendment application.

(iv) Approximately 15–20 cm less water requirement compared to gypsum (no additional leaching required and salt–released is leached with water used for rice crops).

(v) Higher benefit–cost ratio and less pay–back period.

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ICAR-CSSRI/Karnal/Technology Folder/2023/04

Reclamation of Sodic Soils through Elemental Sulphur based formulations

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Karnal (Haryana)
Reliance Industries Limited
Mumbai (Maharashtra)

Soil sodicity is serious abiotic stress affecting crop production in several countries. In India, sodic soils account for ~3.77 m ha. The sodic soil area of country is likely to expand further because of increased usage of the high SAR (sodium adsorption ratio) and RSC (residual sodium carbonate) water. Sodic soils also known as 'alkali soils' carry disproportionately high quantity of sodium (Na^+) than calcium (Ca^{2+}) and magnesium (Mg^{2+}) in the soil exchange sites and in the soil solution. Sodic soils have an exchangeable sodium percent (ESP) > 15%, pH_s > 8.2 and having variable electrical conductivity (EC_e). These soils have poor physical health with greater clay dispersion, less pore space, limited water and air entry (impaired hydraulic conductivity) and storage. The alkaline pH also increases the possibility of loss of organic matter. The excess appearance of Na^+ and precipitation of Ca^{2+} as insoluble $CaCO_3$ further exacerbate the Na^+ induced toxicity and nutritional deficiency in crops.

Gypsum resource status

Gypsum based sodicity reclamation is the flagship technology used for the reclamation of about 2.1 m ha sodic land in India. Around 4.3 million metric tons of gypsum was mined in the year 2022 (Statista, 2023). The gap in demand and supply for different sectors were fulfilled by the utilization of phosphogypsum and gypsum import. The declining quality gypsum reserve in the country and increasing demand of mineral gypsum by other sectors have necessitated the search of new amendment and technology for reclamation of sodicity. Taking the general recommendation of fifty per cent of 12–15 t ha^{-1} for reclamation of top fifteen cm soil layer, country may need a total supply of more than 32–45 million tonnes of gypsum with seventy percent purity. This requirement is expected to increase further due to development of sodicity in new areas under irrigation with sodic (RSC) water.

Elemental S (S°): alternate reclamation agent

Elemental S (S°) is available in India from petrochemical refineries as a by–product. The novel elemental S (S°)–based formulations termed as "RFS" (Patent no. elemental S base reclaiming agent, Indian Patent Application No. 201721041889, Date of Filing: November 23, 2017; US Patent Application No: US 2020/0354285A1, Date: Nov 12, 2020) was used for reclamation of soil sodicity under the collaborative research project between ICAR–CSSRI and Reliance Industries Ltd, Mumbai. The RFS comprises > 90% (w/w) of elemental sulphur (S°). The oxidation of S° in high pH soil is mediated by *heterotrops* under warm, well aerated and moist soil.

$2S° + 3O_2 = 2SO_3$ (microbiological oxidation)

$SO_3 + H_2O = H_2SO_4$

In the initial neutralization stage the H_2SO_4 produced not only change the $NaHCO_3$ to the less harmful and leachable sodium sulphate (Na_2SO_4) but also decreases the pH.

$NaHCO_3 + H_2SO_4 = Na_2SO_4$ (leachable) $+ H_2O + CO_2$

$Na_2CO_3 + H_2SO_4 = Na_2SO_4$ (leachable) $+ H_2O + CO_2$

Na^+–[Soil]–$Na^+ + H_2SO_4 = H^+$–[Soil]–$H^+ + Na_2SO_4$ (leachable)

In quick succession the S° furnishes Ca^{2+} (soluble) indirectly with reacting native soil lime ($CaCO_3$). The release Ca^{2+}_{sol} performed the exchange reaction with Na^+ on the clay complex.

$CaCO_3 + H_2SO_4 = CaSO_4 + H_2O + CO_2$

Na^+–[Soil]–$Na^+ + CaSO_4 = Ca^{2+}$-[Soil]$+ Na_2SO_4$ (leachable)

The advantages of these reactions are the sodium carbonate and bicarbonate change to sodium sulphate, a mild neutral salt and both the carbonate and bicarbonate anions are removed from the system. When, gypsum is used, a portion of carbonate and bicarbonate may remain in soil for long–time.

Elemental sulphur (S°) (RFS) oxidation kinetics

About 80–90% of applied S° was oxidized within 150 days in different sodic soils of pH_s 9.2–10.6 under laboratory incubation conditions. The rate of oxidation varied with soil types and inherent sodicity. All the soils showed appreciable oxidation of S° since the beginning of the incubation. A varying amount of acidity was released in different soils due to oxidation of S°. Acidity production was in the order of Barwah (Khargone) followed by Shivri (Lucknow), Dharamgarh (Panipat) and Haibatpur (Karnal) soil (Table 1). This exchange reaction lead to decline in the proportion of the Na^+ present on exchange complex of the soil by divalent cations (Fig. 1) which help in the improvement in soil physical and chemical properties required for growing crop plants.

Table 1. Effect of RFS application on production of total acidity (me kg^{-1} soil) during S° oxidation after 150 days of incubation (DAI)

Treatment	Shivri, Lucknow	Haibatpur, Karnal	Dharamgarh, Panipat	Barwah, Khargone
Initial pH_s	10.7	9.1	9.4	9.2
RFS 50GR	102.1	40.2	54.5	119.6
RFS 75GR	122.8	59.9	64.9	180.2
RFS 100GR	156.5	71.5	76.3	213.3

GR: percent of gyspsum required

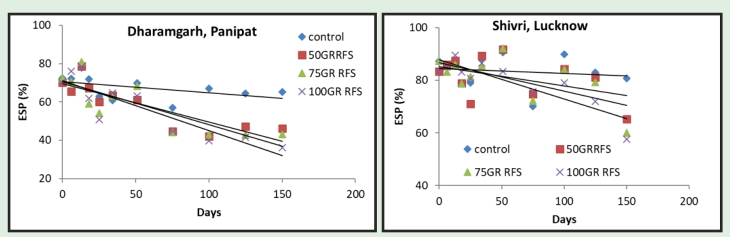

Fig 1. Change in ESP of the RFS treated soil after 150 DAI

Crop response

Performance of the RFS was evaluated in experimental and farmers' field in different agro–ecologies. These sites were distributed in Punjab, Haryana, Uttar Pradesh, Rajasthan and Madhya Pradesh. The observed yield advantage on these sites were mainly because of the neutralization alkalinity and reduction of soil sodicity. Depending upon the severity of sodicity, RFS application caused 8–225% increase in crop yield compared to unreclaimed soils. Application of RFS also caused 0.6–1.5 unit decrease in soil pH after one season of the amendment application (Fig. 2).

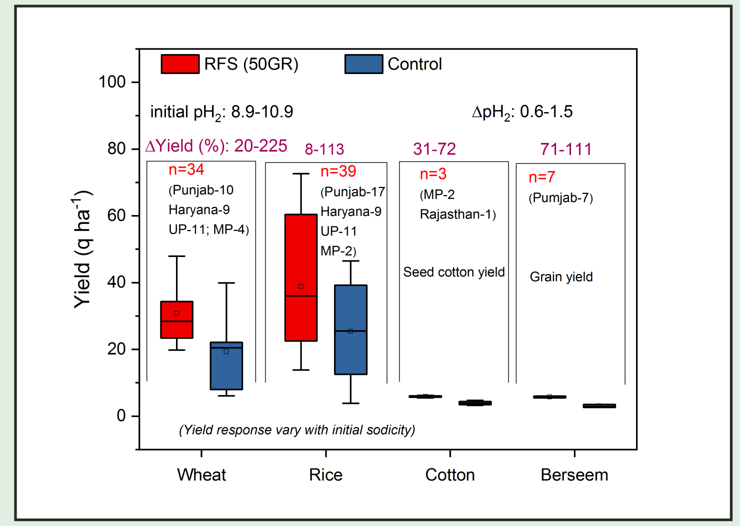

Fig 2. Effect of RFS application on the crop yield and soil pH in different agroecologies

Effect of amendments on soil properties in different agroecologies

Field experiments with RFS at farmers' field affected the crop performance by changing different chemical, physical and biological properties. Different doses of RFS applied lead to solubilization of $CaCO_3$ to release native Ca for reclamation of these soils. This was evident from the decline in $CaCO_3$ content (Table 2). These changes were also associated with a decrease in ESP and an increased in the Walkley–Black organic carbon (WBOC). Decline in ESP because of the RFS application vary with soil types. Besides, the changes in soil chemical properties amended soils also showed a reduction in soil bulk density and increase in hydraulic conductivity. Amendments effects were modified by the irrigation water used. RSC water causes precipitation of the Ca^{2+}_{sol} with net effect of increased sodication and raised soil pH. In good quality irrigated soil pH was stabilized about 500 days after amendment application in Karnal (Fig. 3). Whereas, RSC irrigation increased pH and reached near initial condition after 26 and 36 months in gypsum and RFS treated soils, respectively at Mundri, Kaithal.

Table 2. Effect RFS and gypsum application on soil properties in different agroecologies

Sites	Treatment	pH_s	EC_e (dS m^{-1})	ESP (%)	$CaCO_3$ (%)	WBOC (g kg^{-1})	Bulk density (Mg m^{-3})
Patiala	Control	8.90	2.1	76.6	2.92	5.89	1.32
	Gypsum	8.33	9.9	47.9	2.76	5.90	1.28
	RFS	8.19	6.8	42.1	2.02	6.45	1.30
Kaithal	Control	8.56	1.9	36.8	1.54	5.12	1.65
	Gypsum	7.73	3.8	15.1	1.23	6.29	1.63
	RFS	7.31	2.2	17.4	1.31	6.44	1.62
Etah	Control	9.83	3.6	68.9	1.62	1.72	1.58
	Gypsum	9.41	2.5	55.3	1.60	1.90	1.52
	RFS	8.66	2.7	40.9	0.8	2.88	1.44
Barwah	Control	8.73	5.7	43.9	8.27	5.69	1.36
	Gypsum	8.50	7.2	23.5	10.28	6.5	1.34
	RFS	8.46	4.8	32.1	7.36	5.06	1.33

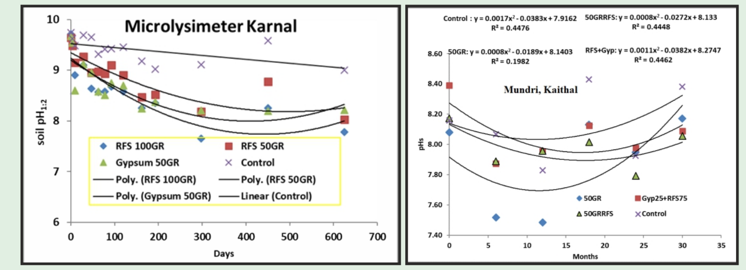

Fig 3. Effect of water quality on change in soil of the sodic soil after application amendments: Karnal - good quality water; Mundari - RSC water

Tailored formulation for specific soil types

Several fields and incubation studies conducted during the investigation showed that three types of formulation could be successfully applied in different parts of the country (Table 3). Besides other soil properties, the calcium carbonate content of the soil was found most important parameter to decide the type of formulation to be recommended for different soils.

Table 3. The formulations are mentioned below with suitable niche

Category of formulations	Formulations	Suitability
CSSRI–RIL formulation I	GypRCFS10, CalRCFS10	Suitable for sodic soils with low (<1.0%) $CaCO_3$ content in Punjab, Haryana, UP, and Bihar (1.79 mha)
CSSRI–RIL formulation II	GypRCFS5, GypRCFS5	Suitable for sodic soils having medium (1–2%) $CaCO_3$ content in Punjab, Haryana, and parts of UP (1.68 m ha)
CSSRI–RIL formulation III	RFS, SAP–II	Suitable for sodic soil with high (>2.0%) $CaCO_3$ in MP, Maharastra, Telangana, TN, Rajasthan, AP, Karnataka (~1.98 mha)

Description of the application protocol

The RFS based reclamation is highly dependent upon the availability of a conducive environment for oxidation of S° to sulphate form to produce sulphuric acid through a biological process. Therefore, exposed surface area, aeration, moisture availability, suitable substrate and effective population of the S° oxidizers are the important factor affecting faster reclamation. The following steps are identified based on experimental findings and testing in field conditions:

- All the reclamation work should be carried out in *pre–kharif* season
- Field levelling and soil sampling for determining the RFS requirement (gypsum requirement estimated in the laboratory).
- The RFS requirement is five times less than the gypsum requirement determined in the laboratory. The 50% RFS requirement was most effective dose for the reclamation