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Effect of Phosphogypsum and $CaCl_2$ Amendments on Reclamation of Saline-Sodic soil in Rice - Wheat Cropping Sequence

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Abstract

Saline–sodic soils constitute a major limitation to agricultural productivity in coastal regions, where elevated concentrations of soluble salts and exchangeable sodium adversely affect soil physico-chemical properties and significantly reduce crop yields. Phosphogypsum (PG) is widely utilized as a reclamation amendment; however, the integration of more soluble calcium sources

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such as calcium chloride ($CaCl_2$) may enhance sodium displacement and accelerate improvements in soil quality. In order to address this, a field study was conducted at Coastal Soil Salinity Research Station, Navsari Agricultural University, Danti, Gujarat (India), to assess the impact of different PG and $CaCl_2$ levels on the reclamation of saline-sodic soils. The field experiment was conducted over a period of three consecutive years (2021-22 to 2023-24) under a rice–wheat cropping sequence, employing a randomized block design (RBD) with four replications. The treatments consisted of seven amendment levels viz., T_1: Control (no amendment), T_2: 75% GR through PG, T_3: 75% GR through $CaCl_2$, T_4: 37.5% GR through PG + 37.5% GR through $CaCl_2$, T_5: 18.75% GR through PG + 56.25% GR through $CaCl_2$, T_6: 56.25% GR through PG + 18.75% GR through $CaCl_2$ and T_7: 65.62% GR through PG + 9.38% GR through $CaCl_2$ with each treatment replicated four times. The results revealed that application of 56.25% GR of PG along with 18.75% GR of $CaCl_2$ during land preparation of *kharif* rice for getting higher rice-wheat yield and net income. Application of PG with $CaCl_2$ was found to reduce soil sodicity.

Keywords: Calcium chloride; Phosphogypsum; rice; Saline-Sodic soil; Wheat.

1. Introduction

Salt-affected soils are characterized by elevated levels of soluble salts (saline) or excessive exchangeable sodium ions (sodic) which pose significant challenges to plant development by disrupting water uptake, nutrient availability, and soil structure. These soils are prevalent across the globe, particularly in arid zones where evaporation exceeds precipitation, and in coastal regions where seawater intrusion or poor drainage exacerbates salinity issues. According to the FAOs global map, salt-affected soils occupy more than 1,381 million hectares of land, equivalent to approximately 10.7 percent of the earth’s terrestrial surface are affected by salinity and sodicity (FAO, 2024). Salinity and sodicity are among the most serious soil degradation problems limiting agricultural productivity in irrigated and coastal regions of India. Approximately 6.74 million ha of land in India is salt-affected, of which 2.22 million ha lies in Gujarat, largely due to sea-water ingress, shallow saline groundwater and poor drainage conditions (Rao *et al*., 2019, ICAR-CSSRI, 2021 and Government of Gujarat, 2020). Soil salinization is a persistent and recurrent phenomenon in complex coastal physiographic regions, including alluvial, aeofluvial, deltaic, coastal plains, mudflats, and mangrove swamps (Yu *et al*., 2024). The principal drivers of salt accumulation in these landscapes include seawater intrusion into coastal plains, deposition of salts in deltaic environments, hydraulic connectivity of drainage channels with saline seawater, and the presence of inherently saline parent materials. Other contributing factors include the predominance of brackish or low-quality groundwater, sporadic seawater flooding in mangrove ecosystems, inadequate drainage infrastructure, and the lack of fresh groundwater resources for effective salt leaching and flushing during the dry season (Sun *et al*., 2025).

In South Gujarat, saline-sodic soils with a high clay content are characterized by an excess of soluble salts and a high exchangeable sodium percentage (ESP). According to Dong *et al*. (2022), Li *et al*. (2023), Patil *et al*. (2023), structural disintegration, reduced hydraulic conductivity, limited root growth, and clay dispersion and swelling, these factors limit soil pore volume and soil-water-air relations. These changes have the potential to significantly reduce microbial growth, nutrient availability, and agricultural productivity (Cai *et al*., 2021). The rice-wheat cropping sequence, which is the most common system in South Gujarat, is especially affected negatively. In rice, puddling damages the soil's physical structure and promotes the buildup of sodicity, which hinders the growth of wheat thereafter (Korav *et al*., 2024).

Chemical amendments that supply soluble calcium are the most effective means to reclaim saline-sodic soils. Calcium replaces exchangeable sodium (Na^+) on soil colloids, thereby improving flocculation, soil structure, infiltration and leaching of salts (Qadir *et al*. 2014, Khan *et al*, 2019). It provides a sustained release of Ca^{2+} to restore soil chemical and physical properties. Phosphogypsum (PG) is rich in calcium sulfate dihydrate ($CaSO_4 \cdot 2H_2O$), a highly effective soil amendment that has been extensively applied to reclaim saline–sodic and improve crop yield. It enhances calcium and sulfur availability, improves soil structure, and supports sustainable agriculture (Nayak *et al*., 2013). India generates around 11–12 million tonnes of phosphogypsum each year. However, in fine-textured soils of South Gujarat, gypsum dissolution and amelioration may be slow due to restricted percolation and poor drainage (Chernysh *et al*., 2025).

Calcium chloride ($CaCl_2$) a highly soluble calcium salt offers rapid Ca^{2+} release and accelerates sodic soil reclamation by quickly reducing ESP and improving soil permeability. Its use lowers clay dispersion and crusting by increasing the electrolyte concentration in the soil solution (Zhang *et al*. 2021). However, chloride ions may result in temporary salinity, requiring sufficient leaching. Numerous studies have shown that combining phosphogypsum and $CaCl_2$ can increase reclamation efficiency by rapidly and sustainably delivering calcium, particularly in Indian soil and water conditions (Gharaibeh *et al*. 2014). The rate and efficiency of water infiltration are significantly higher when calcium sulfate ($CaSO_4$) is applied alone than when it is coupled with either calcium chloride ($CaCl_2$) or sulfuric acid (H_2SO_4) as soil amendments. In certain soil conditions, particularly when water inflow is severely restricted, the use of $CaSO_4$ alone might not be adequate. The use of amendment combinations is advantageous because it can reduce the overall amount of amendment needed while taking advantage of the unique solubility and reactivity advantages of H_2SO_4 or $CaCl_2$ (Prather *et al*. 1978).

This study therefore evaluates the effectiveness of phosphogypsum and $CaCl_2$ amendments, singly and in combination for reclamation of saline–sodic soils under a rice-wheat cropping sequence in South Gujarat (India), aiming to provide evidence-based guidance for farmers and extension agencies on amendment selection and application practices that optimize soil recovery and crop productivity. Furthermore, even though dual amendments like phosphogypsum and calcium chloride have shown encouraging outcomes, there is still a significant information lack about how to optimize amendment quantities for various soil types and salinity–sodicity levels. Current studies often rely on empirical application rates, yet the dose–response relationships between amendment concentration, soil chemical changes and plant growth outcomes are not fully understood. Addressing these gaps will be critical for developing site-specific, cost-effective reclamation strategies in coastal salt affected soils that maximize crop productivity while minimizing environmental risks.

2. Materials and Methods

The Coastal Soil Salinity Research Station, Danti substation of Navsari Agricultural University, Gujarat, India, was the site of the three-year experiment. The station lies 500 meters from the sea and 30 kilometers from Navsari. The soil was categorized as *Typic Natrustalf* and had a texture like a clay loam. Table 1 lists the initial characteristics of the soil. The climate of this region is characterized by fairly hot summer, moderately cold winter, humid and warm monsoon. The area receives an annual average rainfall of 1100 mm, most of which occurs from the second week of June to last week of September. The mean minimum and maximum temperatures vary from 13.8 to 27.2°C and 25.4 to 37.4°C, respectively. The treatments included were T_1: Control (no amendment), T_2: 75% GR through PG, T_3: 75% GR through $CaCl_2$, T_4: 37.5% GR through PG + 37.5% GR through $CaCl_2$, T_5: 18.75% GR through PG + 56.25% GR through $CaCl_2$, T_6: 56.25% GR through PG + 18.75% GR through $CaCl_2$ and T_7: 65.62% GR through PG + 9.38% GR through $CaCl_2$. The trial was designed using a randomized block design, with four replications of each treatment. The treatments were applied to *kharif* rice and their residual effect was studied in the subsequent *rabi* wheat in a year. During all three years the experimental field were different. The gypsum source used was powdered form of phosphogypsum, while for $CaCl_2$, commercial grade was procured locally. The analysis of both these Ca amendments sources used in the experiment is given in table 2. Gypsum requirement of soil was determined before initiation of the experiment and spread over soil and mixed in top (0-12 cm depth). A light irrigation was given and kept for 48 hours and latter flushed with irrigation water. Calculation of the calcium equivalent for each treatment is based on 197 kg/t of calcium contained in phosphogypsum (analysis shows 19.7% Ca^{+2} in the phosphogypsum source) and 241 kg/t of calcium in $CaCl_2$. That is 1 ton of gypsum equivalent to 0.817 ton of $CaCl_2$. Here in the experiment we have considered application of 80% of $CaCl_2$ of the gypsum requirement calculated for phosphogypsum. The rice variety grown was GNR 3 and for wheat it was GW 496. Both these varieties are widely grown by the farmers in this region. The recommended dose of fertilizers applied for *kharif* rice was 120 kg N and 30 kg P_2O_5 per hectare and for wheat 180 N and 90 kg P_2O_5 per hectare.

Table 1. Initial soil properties

	Parameters	2021-22		2022-23		2023-24	
		0-15 cm	15-30 cm	0-15 cm	15-30 cm	0-15 cm	15-30 cm
1.	$pH_{2.5}$	8.87	9.06	8.81	8.93	8.76	9.02
2.	$EC_{2.5}$ (dS/m)	0.69	0.87	0.83	0.89	1.31	1.19
3.	Organic carbon (%)	0.39	0.36	0.44	0.40	0.48	0.42
4.	$CaCO_3$	10.07	10.63	9.92	10.13	8.27	8.91
5.	ESP	18.78	20.78	16.11	18.48	14.81	16.78
6.	Available N (kg/ha)	198	178	225	200	215	183
7.	Available P_2O_5 (kg/ha)	137	120	122	102	117	80
8.	Available K_2O (kg/ha)	2170	2615	2009	2117	1356	1514
9.	Gypsum applied (t/ha)	2021-22	2022-23		2023-24	Mean	
	GR @ 75% Phosphogypsum	7.50	5.82		5.15	6.15	
	$CaCl_2$	6.00	4.65		4.12	4.92	

Table 2. Composition of Phosphogypsum and $CaCl_2$

Particulars	Phosphogypsum	$CaCl_2$
N (%)	ND	ND
P (%)	0.903	0.004
K (%)	0.031	0.011
Ca (%)	19.72	24.17
Mg (%)	1.338	0.563
Na (%)	0.104	0.226
Fe (ppm)	2243.7	80.5
Mn (ppm)	285.7	15.6
Zn (ppm)	23.7	7.8
Cu (ppm)	11.13	8.33

ND: Not detected

The observations were recorded *viz.,* plant height, panicle length, number of effective tillers/sqm, 1000 grain weight, grain yield, straw yield of rice crop and plant height, number of tillers per meter row length, number of spikes per meter row length, number of seed per spike and 1000 grain weight of wheat crop. Before amendments were applied, soil samples were taken from two depths: 0–15 cm and 15–30 cm. They were also taken from each treatment plot following the harvest of rice and wheat. The soil samples were crushed, passed through a 2 mm sieve, and kept in polythene bags with labels. Additionally, soil samples were examined using standard methods to determine their chemical characteristics. Jackson (1973) used to measure the pH of the soil using a pH meter. A conductivity meter was used to determine the soil's electrical conductivity (EC) (Jackson, 1973). Exchangeable Na+ ions were divided by the soil's cation exchange capacity to get ESP, which was then multiplied by 100 (Richards, 1954).

The method appropriate to the Randomized Block Design of the experiment, as outlined by Panse and Sukhatme (1967), was used to statistically analyze the data collected for various characters during the investigation. The F' test was used to determine the significance of the difference. The results' significance was tested using a five percent significance level. When the F' test found that the differences between treatments were significant, the critical differences were computed. Only the standard error of means was calculated in the remaining cases. For each character under investigation, the co-efficient of variance (CV%) was also calculated.

3. Results and Discussion

3.1 Direct Effect of PG and $CaCl_2$ Amendments on Plant Characters of *Kharif* Rice

The results of the plant characters viz., plant height, panicle length, no. of effective tillers/sqm and 1000 grain weight as affected by different levels of PG and $CaCl_2$ amendments pooled over three years are given in table 3. Except no. of effective tiller/ sqm, all the other plant characteristics recorded significantly higher values with application of 18.75% PG+56.25% $CaCl_2$ (T_5).

Plant height of 115.9 cm recorded in treatment T_5 was significantly higher as compared to treatments T_1 (111.4 cm), T_2 and T_3 both having same values of 112.9 cm but remained at par with rest of the treatments. The higher plant height under PG and $CaCl_2$ treatments can be attributed to improvement in soil physical and chemical properties, particularly reduction in soil pH and exchangeable sodium percentage (ESP) and enhanced calcium availability, which together improve root activity and nutrient uptake (Khan *et al*. 2019).

In case of panicle length T_5 (23.6 cm) remained at par with T_6 (23.1 cm), T_7 (23.0 cm) and recorded significant higher value as compared to remaining treatments. The longer panicles under combined PG and $CaCl_2$ treatments suggest better translocation of assimilates to reproductive structures, as the reclamation of sodic soil improves water uptake, ionic balance, and photosynthetic efficiency (Duan *et al*. 2023). The lowest panicle length of 21.5 was achieved from check plots.

The treatment effects were non-significant on the number of effective tillers per square meter of *kharif* rice due to various levels and combinations of PG and $CaCl_2$, although numerical differences were evident among the treatments. The highest number of effective tillers (279 tillers**/** sqm) was observed in treatment T_5 (18.75% PG + 56.25% $CaCl_2$), followed closely by T_6 (56.25% PG + 18.75% $CaCl_2$) and T_7 (65.62% PG + 9.38% $CaCl_2$), which recorded 276 and 275 tillers/sqm, respectively. The lowest number of tillers (252 tillers/sqm) was found in the control (T_1) treatment. The trend unequivocally demonstrated that the combination treatment of PG and $CaCl_2$ encouraged rice tillering when compared to individual applications or the control. An increase in effective tillers under combined PG and $CaCl_2$ treatments is caused by increased soil structure, porosity, and aeration as a result of calcium ions (Ca^{2+}) replacing exchangeable sodium ions (Na^+). This exchange response increases soil aggregation and water infiltration by promoting the flocculation of clay particles, creating a more favorable environment for root development and nutrient uptake. Similar positive effects of calcium additions on rice growth parameters in sodic soils were found by Zhao *et al*. (2020), who discovered that both gypsum and $CaCl_2$ enhance the physical properties of sodic soils and encourage strong plant establishment.

The treatment T_5 reported a higher 1000 grain weight of 27.1 g, which was judged to be significant over the other treatments and comparable to treatments T_6 and T_7, all of which recorded the same value of 27.0. According to Hasana *et al*. (2022), the increase indicates improved grain filling under favorable soil chemical circumstances because the amendments raise the concentration of Ca^{2+} in the soil solution and decrease the toxicity of Na^{2+}, which improves carbohydrate translocation and grain maturity. The lowest 1000 grain weight of 23.8 g was recorded from control.

The combined treatment T_5 (18.75% PG + 56.25% $CaCl_2$) consistently recorded the highest values for most growth and yield attributes. The superiority of this treatment could be due to the complementary roles of PG (providing sustained calcium release) and $CaCl_2$ (providing immediate soluble calcium), leading to rapid reclamation and long-term soil improvement. Similar observations were also reported by Gharaibeh *et al*. (2009).

3.2 Direct Effect of PG and $CaCl_2$ Amendments on Grain and Straw Yield of *Kharif* Rice

The data given in table 4 represents year wise and pooled results of grain and straw yields of *kharif* rice as affected by different levels of PG and $CaCl_2$. The yields of both rice grain and straw were significantly influenced due to application of these calcium amendments.

During first year (2021), treatment T_5, i.e. application of 18.75% GR of PG+56.25% GR of $CaCl_2$ recorded significant higher grain (5273 kg/ha) as compared to T_1 - control (3887 kg/ha) and T_3 -75% GR of $CaCl_2$ (4574 kg/ha). During subsequent two years (2022 and 2023), treatment T_6 - 56.25% GR of PG+18.75% GR of $CaCl_2$ recorded significant higher rice grain yield of 4388 kg/ha and 4719 kg/ha, respectively as compared to T_1 during 2022 and T_1 and T_3 during 2023, but remained at par with rest of the treatments. In pooled results, T_6 recorded significant higher grain yield (4778 kg/ha) as compared to T_1 but which was comparable to treatments T_4, T_5 and T_7. The decrease in soil exchangeable sodium percentage (ESP) and electrical conductivity (EC), which improves soil structure, aeration, and nutrient uptake by the rice crop, may be the reason for the increase in grain production caused by the application of PG and $CaCl_2$. Phosphogypsum provides a continuous supply of soluble Ca^{2+} which replaces exchangeable Na^+, while $CaCl_2$ enhances leaching of Na^+ through improved flocculation of soil particles The synergistic effect observed in combined treatments indicates balanced ionic activity in the rhizosphere and better root proliferation (Gharaibeh *et al*. 2009 and Singh *et al*. 2016).

The results of straw yield of rice indicated that during 2021, significant higher straw yield was recorded with treatment T_5 (6665 kg/ha) as compared to T_1 (4794 kg/ha) and T_3 (5639 kg/ha). In the year 2022, higher straw yield was recorded in T_6 treatment (5664 kg/ha) as compared to T_1-control (3729 kg/ha), but remained at par with remaining treatments. In the subsequent year (2023), higher straw yield was recorded in T_6 (5988 kg/ha) as compared to T_1 (4524 kg/ha) and T_3 (5187 kg/ha). In pooled analysis significant higher straw yield (6099 kg/ha) was recorded in treatment T_6 (56.25% GR of PG+18.75% GR of $CaCl_2$) as compared to T_1 (4349 kg/ha), T_2 (5634 kg/ha) and T_3 (5311 kg/ha), but remained at par with rest of the treatments. The increased straw yield in amendments treated plots might be due to improved soil physical conditions, which facilitated better root growth and nutrient uptake, thereby enhancing vegetative biomass (Singh *et al*. 2022). The enhanced performance of PG and $CaCl_2$ treatments may also be linked to improved Ca:Na ratios, which mitigate the adverse effects of Na toxicity on plant metabolism and photosynthetic activity (Rahman *et al*. 2016). The balanced use of both amendments appears more effective in maintaining optimal soil chemistry and plant growth conditions compared to single applications.

3.3 Residual Effect of PG and $CaCl_2$ Amendments on Plant Characters of *Rabi* Wheat

The results pertaining to three years pooled parameters of plant characters recorded at harvest of subsequent *rabi* wheat crop are given in table 5. The pooled data revealed that the residual effect of PG and calcium chloride ($CaCl_2$) amendments applied in the preceding *kharif* rice crop influenced the plant height of the succeeding *rabi* wheat crop, though the differences among treatments were statistically non-significant. Although, the highest plant height (78.5 cm) was recorded in treatment T_6 (56.25% PG + 18.75% $CaCl_2$), closely followed by T_7 (65.62% PG + 9.38% $CaCl_2$) and T_5 (18.75% PG + 56.25% $CaCl_2$), whereas the lowest height (74.6 cm) was observed in the control (T_1). This improvement in plant height can be attributed to the improved soil physical and chemical conditions due to the residual effects of Ca^{2+} ions that replaced exchangeable Na^+ in saline-sodic soils. The enhanced soil structure and reduced sodicity improved root growth and nutrient availability for the succeeding wheat crop. Similar observations were reported by Nayak *et al*. (2013) and Murtaza *et al*. (2017).

The number of tillers per meter row length of *rabi* wheat was statistically non-significant **(**Table 5). The highest number of tillers (81.8) was recorded under treatment T_7 (65.62% PG + 9.38% $CaCl_2$), followed closely by T_5 (18.75% PG + 56.25% $CaCl_2$) and T_6 (56.25% PG + 18.75% $CaCl_2$), indicating that the combined application of PG and $CaCl_2$ tended to improve tiller formation compared to the control (74.4). The control (T_1) treatment exhibited the lowest value, indicating that the residual calcium from soil amendments continued to improve the soil environment for improved crop growth. The greater replacement of exchangeable sodium ions (Na^+) by calcium ions (Ca^{2+}), which enhances soil structure, porosity, and aeration, may be the cause of an increase in tiller number under combined PG and $CaCl_2$ treatments. Similar findings were reported by Zhao *et al*. (2020).

The trend for the number of spikes per meter row length was nearly identical to that of plant height (Table 5). Treatments T_5 (18.75% PG + 56.25% $CaCl_2$) showed greater values (75.3 spikes) than the control (65.1 spikes). At the 5% level, the spike number showed a significant response. The continued increase in soil nutrient status, especially calcium availability, which improves tiller initiation and survival, may be the cause of greater number of spikes. By substituting Ca^{2+} ions for exchangeable Na^+ ions, soil aeration and microbial activity are enhanced, which indirectly promotes spike production and plant establishment. These results are in line with research by Salim *et al*. (2002).

The number of seeds per spike of *rabi* wheat was statistically non-significant because to the residual effect of different combinations of PG and calcium chloride ($CaCl_2$) (Table 5). Nonetheless, numerical variations were noted among the treatments. The maximum number of seeds per spike (81.8) was recorded under treatment T_7 (65.62% PG + 9.38% $CaCl_2$), closely followed by T_5 (18.75% PG + 56.25% $CaCl_2$) and T_6 (56.25% PG + 18.75% $CaCl_2$), which recorded 81.5 and 81.1 seeds per spike, respectively. The control (T_1) had the lowest value (74.4 seeds per spike). This pattern indicates that the quantity of seeds per spike of *rabi* wheat was positively impacted by the combined treatment of PG and $CaCl_2$. This enhancement points to a positive long-term impact of calcium additions on wheat reproductive development. In addition to improving soil pH and nutrient intake, gypsum and $CaCl_2$ also boost photosynthetic efficiency and assimilate translocation to growing grains (Rahman *et al*. 2016).

The residual effect of amendments had significant effects on the 1000-grain weight (Table 5). The highest 1000-grain weight (47.1 g) was recorded under T_5 (18.75% Gypsum + 56.25% $CaCl_2$), which was significantly superior to all other treatments. The lowest 1000-grain weight (42.7 g) was observed in the control. The increase in 1000 grain weight under amended treatments may be due to improved nutrient uptake efficiency, particularly calcium and sulfur, leading to better grain filling. Calcium plays an essential role in cell wall stabilization and enzyme activity, which positively affects grain formation and quality (Khan *et al*. 2007, Shah *et al*. 2013 and Roa *et al*. 2024).

3.4 Residual Effect of PG and $CaCl_2$ Amendments on Grain and Straw Yield of *Rabi* Wheat

The results of the *rabi* wheat grain and straw yield given in table 6 revealed that, during 2021-22, significant higher wheat grain yield (3026 kg/ha) was recorded in treatment T_5 as compared to T_1 (1971 kg/ha) and T_3 (2535 kg/ha). During subsequent two years, treatment T_6 recorded significant higher grain yield of 3324 kg/ha during 2022-23 and 3867 kg/ha during 2023-24 as compared to control during both the years. In pooled results, significant higher wheat grain yield was recorded in T_6 (3371 kg/ha) which was due to the residual effect of 56.25 % PG + 18.75 % $CaCl_2$. The higher residual grain yield under combined treatments (T_5 and T_6) indicates that integrated use of PG and $CaCl_2$ not only improved soil conditions for the rice crop but also sustained their beneficial effects for the succeeding wheat crop. This could be due to the prolonged improvement in soil physical properties, reduction in exchangeable sodium percentage (ESP) and maintenance of a favourable Ca^{2+}: Na^+ ratio, leading to better nutrient uptake and root development (Khan *et al*. 2007 and Rasouli *et al*. 2013).

The results of straw yield of wheat indicated that during 2021-22, significant higher straw yield was recorded with treatment T_5 (4427 kg/ha) as compared to T_1 (2906 kg/ha), T_2 (3780 kg/ha) and T_3 (3695 kg/ha). In the year 2022-23, higher straw yield was recorded in T_6 treatment (4741 kg/ha) as compared to T_1 (3151 kg/ha), T_2 (4024 kg/ha) and T_3 (3823 kg/ha) but remained at par with remaining treatments. In the subsequent year (2023-24), higher straw yield was recorded in T_6 (5272 kg/ha) as compared to T_1 (3150 kg/ha). In pooled analysis significant higher straw yield (4723 kg/ha) was recorded in treatment T_6 as compared to T_1 (3069 kg/ha), T_2 (4220 kg/ha) and T_3 (4140 kg/ha) but remained at par with rest of the treatments. The increase in straw yield under PG and $CaCl_2$ treatments can be attributed to better plant growth and higher biomass accumulation, supported by improved soil aeration and nutrient availability. PG application provides a continuous supply of Ca^{2+}, which replaces exchangeable Na^+, resulting in improved root proliferation and nutrient translocation. $CaCl_2$, on the other hand, enhances the leaching of soluble salts and sodium through its high solubility. Their combined use improves the soil's physical and chemical environment for longer periods, leading to enhanced vegetative growth even in the succeeding crop. Similar residual benefits of gypsum and calcium salt amendments on wheat straw yield and soil productivity under sodic soils have also been reported by several researchers (Gharaibeh *et al*. 2009 and Salim *et al*. 2002).

3.5 Rice Grain Equivalent Yield (RGEY)

Table 7 shows the yield data for wheat and rice, reported as rice grain equivalent yield affected by the application of various PG and $CaCl_2$ levels in the saline-sodic soil. During 2021-22, significant higher RGEY (11602 kg/ha) was recorded with application of 18.75% GR of PG + 56.25% GR of $CaCl_2$ (T_5) as compared to T_1, T_2 and T_3. In the subsequent two years significant higher RGEY was recorded in treatment T_6 (56.25% PG+18.75% $CaCl_2$) i.e., 10925 kg/ha during 2022-23 and 12152 kg/ha during 2023-24 as compared to T_1, T_2 and T_3. Similarly, in pooled result also treatment T_6 recorded higher RGEY of 11486 kg/ha which being at comparable with T_5 (11339 kg/ha) recorded significantly higher RGEY over rest of the treatments.

The improvement in RGEY under the combined use of PG and $CaCl_2$ indicates a synergistic effect of these amendments in ameliorating saline-sodic soils, which led to improved productivity of both rice and wheat crops. These sources of soluble calcium contributed to the replacement of exchangeable sodium, the reduction of soil sodicity, the improvement of soil structure, and the enhancement of water and nutrient uptake. Higher system productivity was the outcome of these effects that lasted throughout the cropping sequence. These findings are consistent with those of Nayak *et al*. (2013), Ram *et al*. (2016) and Murtaza *et al*. (2017).

3.6 Soil Properties

The results pertaining to soil properties at depth (0-15 and 15-30 depth) were analyzed for $pH_{2.5}$, $EC_{2.5}$ and ESP after harvest of crops are given in tables 8, 9 and 10, respectively.

Soil $pH_{2.5}$: After harvest of *kharif* rice. After the harvest of *kharif* rice in all three years (2021 to 2023), the data in Table 8 showed that the application of various amounts and combinations of PG and $CaCl_2$ significantly influenced soil $pH_{2.5}$ at both surface (0–15 cm) and subsurface (15–30 cm) layers.

During first year (2021), soil $pH_{2.5}$ ranged from 8.56 to 8.92 at 0-15 cm soil depth and 8.68 to 9.07 at 15-30 cm soil depth, with the highest values recorded in T_1 (control) and the lowest in T_5 (18.75% PG + 56.25% $CaCl_2$). A similar decreasing trend in soil pH was observed in subsequent years. During third year (2023), surface soil pH decreased to 8.46 in T_5, compared to 8.77 in the control, representing an overall reduction of 0.31 units. When PG and $CaCl_2$ are applied, exchangeable sodium (Na^+) is replaced by calcium (Ca^{2+}), which promotes the formation of soluble sodium salts that are subsequently leached from the soil profile. This could be the reason for the decrease in soil $pH_{2.5}$. The electrolyte concentration is also raised by the dissolution of Ca^{2+} from PG and $CaCl_2$, which reduces Na^{2+} dispersion and enhances soil structure. Gypsum and $CaCl_2$ worked better when used together than those used separately. Because of its greater solubility and quicker release of Ca^{2+} ions, T_5 (18.75% PG + 56.25% $CaCl_2$) had the lowest soil pH of all the combinations in both depths and all years. Similar findings were also reported by Qadir *et al*. (2007) and Gharaibeh *et al*. (2009).

After harvest of *rabi* wheat: The residual effect of PG and $CaCl_2$ application on soil $pH_{2.5}$ showed a continuous declining trend in comparison to the control (Table 8) after the harvest of *rabi* wheat. Soil $pH_{2.5}$ at the surface layer (0–15 cm) varied between 8.41 and 8.96 in 2021–2022, 8.41 and 8.78 in 2022–2023, and 8.32 and 8.83 in 2023–2024. T_5 (18.75% PG + 56.25% $CaCl_2$) consistently had the lowest $pH_{2.5}$. Soil $pH_{2.5}$ showed a similar pattern at the deeper layer (15–30 cm), although the decrease was less noticeable because Ca^{2+} ions moved more slowly downward. The continual release of Ca^{2+} from leftover PG and $CaCl_2$, which continued to replace Na^+ ions during the subsequent *rabi* season, may be the cause of the observed residual reduction in soil $pH_{2.5}$ after wheat. Additionally, more exchangeable salt leaching was probably made easier by irrigation water percolating during the wheat season. The data clearly indicated that soil $pH_{2.5}$ was lower after the harvest of wheat than rice, implying that the reclamation process continues under sequential cropping. The greater residual effect observed in combined treatments suggests that integration of PG and $CaCl_2$ provides both immediate (from $CaCl_2$) and sustained (from phosphogypsum) sources of calcium for ongoing sodic soil amelioration. Qadir *et al*. (2007) and Gharaibeh *et al*. (2009) were also highlighted this effect.

Soil $EC_{2.5}$: After harvest of *kharif* rice**.** The data presented in Table 9 show that soil $EC_{2.5}$ at both soil depths (0-15 cm and 15-30 cm) was influenced by different levels and combinations of gypsum and $CaCl_2$ during 2021 to 2023. Although statistical differences were non-significant across treatments, a general increasing trend in soil $EC_{2.5}$ values was observed with the application of PG and $CaCl_2$ compared to the control (T_1).

During the first year (2021-22), the $EC_{2.5}$ values ranged from 0.72 to 0.96 dS m^{-1} at the surface and 0.93 to 1.25 dS m^{-1} at the subsurface layer. The control (T_1) recorded the lowest $EC_{2.5}$ (0.72 dS m^{-1}), while slightly higher values were observed in gypsum treated plots, which can be attributed to the increased concentration of soluble Ca^{2+} and SO_4^{2-} ions released during gypsum dissolution. Over the subsequent years, $EC_{2.5}$ values ranged from 1.15-1.53 dS m^{-1} at the surface and 1.06 to 1.46 dS m^{-1} at the subsurface layer in 2023-24. The slight increase in $EC_{2.5}$ after amendment application is indicative of improved ion mobility and solubility brought on by the breakdown of PG and $CaCl_2$, which temporarily raises the concentration of salt in the soil solution. However, these soluble salts aid in exchangeable sodium displacement, promoting leaching of Na^+ and eventual reclamation of sodic soil. Similar short-term EC increases following amendments application have been reported by Gharaibeh *et al*. (2014) and Tao *et al*. (2019).

After harvest of *rabi* wheat. The residual effect of PG and $CaCl_2$ on soil $EC_{2.5}$ after the harvest of *rabi* wheat is presented in Table 9. The results revealed non-significant differences among treatments, but observable variations in $EC_{2.5}$ values between treatments.

Generally, soil $EC_{2.5}$ values after harvest of *rabi* wheat were slightly higher than those after rice in the corresponding years. This could be attributed to addition of salts through irrigation water during wheat crop/reduced leaching during the *rabi* season under lower rainfall conditions and increased accumulation of soluble salts near the surface. The EC remained within the safe range (<2.0 dS m^{-1}) across all treatments, confirming that the applied amendments did not cause secondary salinization (Sundha *et al*., 2020).

Soil ESP: After harvest of *kharif* rice. The data in Table 10 showed that over all three years of testing (2021 to 2023) under the rice-wheat cropping sequence, the application of PG and $CaCl_2$ considerably reduced the exchangeable sodium percentage (ESP) of soil compared to the control.

The differences in soil ESP among different treatments were significant after harvest of *kharif* rice during first, second and third years at 0-15 cm soil depth. During 2021 and 2023 years, significantly highest reduction in soil ESP was recorded with treatment T_5 (18.75% PG+56.25% $CaCl_2$) (12.99 and 7.47%) but which was found at par with T_2, T_3, T_4, T_6 and T_7 treatments during 2021 and T_4, T_6 and T_7 treatments during 2023 at 0-15 cm soil depth. During 2022, significantly highest reduction in soil ESP was recorded with application of 56.25% PG+18.75% $CaCl_2$ (T_6) (9.16 %) but which was comparable to T_2, T_3, T_4, T_5 and T_7 treatments at 0-15 cm soil depth. Maximum soil ESP (19.81, 16.01 and 14.98 %) was recorded under the control treatment where neither PG nor $CaCl_2$ was applied at 0-15 cm during first, second and third years, respectively.

At 15-30 cm depth, significant highest reduction in soil ESP was recorded with treatment (T_6) 56.25% Gyp+18.75% $CaCl_2$ (14.74 %) as compared to control treatments, but was found at par with remaining treatments in 2021 year. During 2022 and 2023, significantly highest reduction in soil ESP was recorded with treatment (T_5) 18.75% PG+56.25% $CaCl_2$ (13.31 and 10.34 %) but which was comparable to T_2, T_3, T_4, T_6 and T_7 treatments at 15-30 cm soil depth. Maximum soil ESP (21.43, 19.52 and 16.52 %) was recorded under the control treatment where neither PG nor $CaCl_2$ was applied at 15-30 cm during first, second and third years, respectively.

The reduction in ESP with PG and $CaCl_2$ application is attributed to the replacement of exchangeable sodium (Na^+) by calcium (Ca^{2+}), improving soil aggregation and permeability. The higher efficiency of combined treatments can be ascribed to the better solubility of $CaCl_2$, which provides a rapid source of Ca^{2+}, while gypsum ensures sustained Ca^{2+} release, enhancing reclamation depth and stability. The significant improvement in the upper soil layer (0–15 cm) relative to the subsurface (15–30 cm) is caused by the increasing downward movement of soluble Ca^{2+} and the surface application effect of amendments (Gharaibeh *et al*. 2009).

After harvest of *rabi* wheat. The results shown in Table 10 indicates that the exchangeable sodium percentage (ESP) of soil after the *rabi* wheat harvest in 2021–2022, 2022–2023, and 2023–2024 was greatly impacted by various PG and $CaCl_2$ levels and combinations. As amendments were applied, ESP values consistently and significantly decreased in both soil layers (0-15 cm and 15-30 cm) as compared to the control.

During 2021-22, significantly highest reduction in soil ESP was recorded with treatment T_6 (56.25% PG+18.75% $CaCl_2$) (9.89 %) but which was found comparable to T_2, T_3, T_4, T_5 and T_7 treatments at 0-15 cm soil depth. During 2022-23, significantly highest reduction in soil ESP was recorded with treatment T_7 (65.62% PG+9.38% $CaCl_2$) (7.24 %) but which was comparable to T_2, T_3, T_4, T_5 and T_6 treatments at 0-15 cm soil depth. During 2023-24, significantly highest reduction in soil ESP was recorded with treatment T_5 (18.75% PG+56.25% $CaCl_2$) (6.15 %) but which was found at par with T_2, T_3, T_4, T_6 and T_7 treatments at 0-15 cm soil depth. Maximum soil ESP (19.09, 17.14 and 15.93 %) was recorded under the control treatment where neither PG nor $CaCl_2$ was applied at 0-15 cm during first, second and third years, respectively.

At 15-30 cm depth, significant highest reduction in soil ESP was recorded with treatment T_5 (18.75% PG+56.25% $CaCl_2$) (11.87 and 10.96 %) as compared to control treatments, but was found at par with remaining treatments in 2021-22 and 2022-23. During 2023-24, significantly

Table 3. Direct effect of different levels of PG and $CaCl_2$ on different plant characters of *kharif* rice (Pooled over three years)

Treatment	**Plant height (cm)**	**Panicle length (cm)**	**No. of effective tiller/ sqm**	**1000 grain weight (g)**
T_1- Control	111.4	21.5	252	23.8
T_2- 75% PG	112.9	22.4	270	25.7
T_3- 75% $CaCl_2$	112.9	22.5	261	25.4
T_4- 37.5% PG+37.5% $CaCl_2$	114.2	22.6	273	26.0
T_5- 18.75% PG+56.25% $CaCl_2$	115.9	23.6	279	27.1
T_6- 56.25% PG+18.75% $CaCl_2$	115.2	23.1	276	27.0
T_7- 65.62% PG+9.38% $CaCl_2$	115.8	23.0	275	27.0
Mean	**114.0**	**22.7**	**270**	**26.0**
SEm±	0.87	0.19	6.3	0.30
CD (P = 0.05)	**2.5**	**0.6**	**NS**	**0.9**
CV (%)	2.66	2.94	8.15	4.03

Table 4. Direct effect of different levels of PG and $CaCl_2$ on grain and straw yield of *kharif* rice

Treatment	**Grain yield (kg/ha)**				**Straw yield (kg/ha)**			
	2021	**2022**	**2023**	**Pooled**	**2021**	**2022**	**2023**	**Pooled**
T_1- Control	3887	3004	3660	3517	4794	3729	4524	4349
T_2- 75% PG	4783	4189	4230	4401	6048	5451	5402	5634
T_3- 75% $CaCl_2$	4574	4067	4179	4273	5639	5106	5187	5311
T_4- 37.5% PG+37.5% $CaCl_2$	4974	4114	4390	4493	6279	5265	5652	5732
T_5- 18.75% PG+56.25% $CaCl_2$	5273	4266	4645	4728	6665	5467	5884	6005
T_6- 56.25% PG+18.75% $CaCl_2$	5228	4388	4719	4778	6646	5664	5988	6099
T_7- 65.62% PG+9.38% $CaCl_2$	5221	4126	4377	4574	6480	5190	5627	5766
Mean	**4849**	**4022**	**4314**	**4395**	**6079**	**5125**	**5466**	**5557**
SEm±	215.7	157.2	173.0	106.0	272.6	210.3	230.3	138.1
CD (P = 0.05)	**641**	**467**	**514**	**301**	**810**	**625.0**	**684**	**391**
CV (%)	8.90	7.82	8.07	8.36	8.97	8.21	8.43	8.61

Table 5. Residual effect of different levels of PG and $CaCl_2$ on different plant characters of *rabi* wheat (Pooled over 3 years)

Treatment	**Plant height (cm)**	**No. of tillers/ m row length**	**No. of spikes/m row length**	**No. of seeds per spike**	**1000 grain weight (g)**
T_1- Control	74.6	74.4	65.1	74.4	42.7
T_2- 75% PG	76.4	78.5	70.8	78.5	44.0
T_3- 75% $CaCl_2$	76.4	78.2	70.8	78.2	44.2
T_4- 37.5% PG+37.5% $CaCl_2$	76.2	78.1	71.6	78.1	44.6
T_5- 18.75% PG+56.25% $CaCl_2$	78.2	81.5	75.3	81.5	47.1
T_6- 56.25% PG+18.75% $CaCl_2$	78.5	81.1	74.3	81.1	45.7
T_7- 65.62% PG+9.38% $CaCl_2$	78.3	81.8	74.4	81.8	45.9
Mean	**76.9**	**79.1**	**71.8**	**79.1**	**44.9**
SEm±	1.17	2.00	1.82	2.00	0.39
CD (P = 0.05)	**NS**	**NS**	**5.2**	**NS**	**1.1**
CV (%)	5.28	8.76	8.78	8.11	2.99

Table 6. Residual effect of different levels of PG and $CaCl_2$ on grain and straw yield of *rabi* wheat

Treatment	**Grain yield (kg/ha)**				**Straw yield (kg/ha)**			
	2021-22	**2022-23**	**2023-24**	**Pooled**	**2021-22**	**2022-23**	**2023-24**	**Pooled**
T_1- Control	1971	2371	2434	2259	2906	3151	3150	3069
T_2- 75% PG	2648	2931	3589	3056	3780	4024	4855	4220
T_3- 75% $CaCl_2$	2535	2846	3627	3003	3695	3823	4902	4140
T_4- 37.5% PG+37.5% $CaCl_2$	2761	3132	3652	3182	3967	4379	4901	4415
T_5- 18.75% PG+56.25% $CaCl_2$	3026	3239	3701	3322	4427	4553	5094	4691
T_6- 56.25% PG+18.75% $CaCl_2$	2923	3324	3867	3371	4156	4741	5272	4723
T_7- 65.62% PG+9.38% $CaCl_2$	2679	3215	3686	3194	3938	4559	4933	4477
Mean	**2649**	**3008**	**3508**	**3055**	**3838**	**4176**	**4729**	**4248**
SEm±	136.0	138.3	154.6	82.68	189.5	169.8	219.6	117.5
CD (P = 0.05)	**404**	**411**	**459**	**234**	**563**	**504**	**653**	**333**
CV (%)	10.27	9.19	8.81	9.38	9.87	8.13	9.29	9.58

Table 7. Effect of different levels of PG and $CaCl_2$ on rice grain equivalent yield (kg/ha)

Treatment	**Rice Grain Equivalent Yield (kg/ha)**			
	2021-22	**2022-23**	**2023-24**	**Pooled**
T_1- Control	8122	7567	8504	8064
T_2- 75% PG	10363	10047	11086	10499
T_3- 75% $CaCl_2$	9589	9701	10819	10036
T_4- 37.5% PG+37.5% $CaCl_2$	10788	10247	11401	10812
T_5- 18.75% PG+56.25% $CaCl_2$	11602	10616	11801	11339
T_6- 56.25% PG+18.75% $CaCl_2$	11380	10925	12152	11486
T_7- 65.62% PG+9.38% $CaCl_2$	10966	10377	11433	10925
Mean	**10401**	**9926**	**11028**	**10452**
SEm±	357.2	275.7	335.4	187.4
CD (P = 0.05)	**1061**	**819**	**997**	**531**
CV (%)	6.87	5.56	6.08	6.21

Selling price of rice grain: ₹.18.57/kg; rice straw: ₹.4.5/kg; wheat grain: ₹.26/kg; wheat straw: ₹.2.0/kg; phosphogypsum: ₹.2400/t; $CaCl_2$: ₹.13940/t

Table 8. Effect of different levels of PG and $CaCl_2$ on soil $pH_{2.5}$ after harvest of rice and wheat

Treatment	**2021-22**		**2022-23**		**2023-24**	
***Direct effect* after *kharif* rice**	**0-15 cm**	**15-30 cm**	**0-15 cm**	**15-30 cm**	**0-15 cm**	**15-30 cm**
T_1- Control	8.92	9.07	8.75	8.88	8.77	8.98
T_2- 75% PG	8.65	8.71	8.57	8.70	8.57	8.68
T_3- 75% $CaCl_2$	8.62	8.68	8.54	8.66	8.48	8.65
T_4- 37.5% PG+37.5% $CaCl_2$	8.66	8.69	8.52	8.60	8.54	8.67
T_5- 18.75% PG+56.25% $CaCl_2$	8.56	8.68	8.52	8.59	8.46	8.63
T_6- 56.25% PG+18.75% $CaCl_2$	8.62	8.77	8.60	8.69	8.49	8.63
T_7- 65.62% PG+9.38% $CaCl_2$	8.61	8.72	8.54	8.71	8.54	8.68
Mean	**8.69**	**8.76**	**8.55**	**8.69**	**8.54**	**8.70**
SEm±	0.045	0.048	0.048	0.054	0.055	0.064
CD (P = 0.05)	**0.13**	**0.14**	**0.14**	**0.16**	**0.16**	**0.19**
CV (%)	1.03	1.09	1.12	1.24	1.30	1.47

Treatment	**2021-22**		**2022-23**		**2023-24**	
***Residual effect after rabi* wheat**	**0-15 cm**	**15-30 cm**	**0-15 cm**	**15-30 cm**	**0-15 cm**	**15-30 cm**
T_1- Control	8.96	9.08	8.78	8.99	8.83	8.75
T_2- 75% PG	8.59	8.69	8.52	8.61	8.42	8.49
T_3- 75% $CaCl_2$	8.52	8.65	8.48	8.57	8.39	8.46
T_4- 37.5% PG+37.5% $CaCl_2$	8.53	8.63	8.43	8.62	8.45	8.49
T_5- 18.75% PG+56.25% $CaCl_2$	8.41	8.60	8.41	8.53	8.32	8.44
T_6- 56.25% PG+18.75% $CaCl_2$	8.57	8.71	8.44	8.53	8.37	8.47
T_7- 65.62% PG+9.38% $CaCl_2$	8.54	8.72	8.51	8.59	8.42	8.54
Mean	**8.62**	**8.79**	**8.52**	**8.63**	**8.46**	**8.52**
SEm±	0.047	0.060	0.073	0.050	0.078	0.063
CD (P = 0.05)	**0.14**	**0.18**	**0.22**	**0.15**	**0.23**	**0.19**
CV (%)	1.08	1.38	1.71	1.16	1.83	1.49

Table 9. Effect of different levels of PG and $CaCl_2$ on soil $EC_{2.5}$ (dS/m) after harvest of rice and wheat

Treatment	**2021-22**		**2022-23**		**2023-24**	
***Direct effect after kharif* rice**	**0-15 cm**	**15-30 cm**	**0-15 cm**	**15-30 cm**	**0-15 cm**	**15-30 cm**
T_1- Control	0.72	0.93	0.93	0.91	1.23	1.28
T_2- 75% PG	0.96	1.14	1.07	1.02	1.31	1.24
T_3- 75% $CaCl_2$	0.81	1.08	0.89	0.91	1.15	1.32
T_4- 37.5% PG+37.5% $CaCl_2$	0.81	1.24	0.95	1.16	1.53	1.06
T_5- 18.75% PG+56.25% $CaCl_2$	0.78	1.00	1.03	1.10	1.29	1.33
T_6- 56.25% PG+18.75% $CaCl_2$	0.81	1.21	1.06	1.23	1.44	1.46
T_7- 65.62% PG+9.38% $CaCl_2$	0.87	1.25	1.05	1.20	1.35	1.06
Mean	**0.82**	**1.12**	**1.00**	**1.07**	**1.33**	**1.25**
SEm±	0.067	0.088	0.078	0.086	0.106	0.103
CD (P = 0.05)	**NS**	**NS**	**NS**	**NS**	**NS**	**NS**
CV (%)	16.29	15.66	14.44	16.33	15.92	16.56
Treatment	**2021-22**		**2022-23**		**2023-24**	
***Residual effect after rabi* wheat**	**0-15 cm**	**15-30 cm**	**0-15 cm**	**15-30 cm**	**0-15 cm**	**15-30 cm**
T_1- Control	1.34	1.11	1.57	1.25	1.32	1.39
T_2- 75% PG	1.11	1.06	1.53	1.48	1.36	1.26
T_3- 75% $CaCl_2$	1.11	1.42	1.41	1.37	1.20	1.18
T_4- 37.5% PG+37.5% $CaCl_2$	1.55	1.29	1.46	1.32	1.38	1.24
T_5- 18.75% PG+56.25% $CaCl_2$	1.28	1.08	1.33	1.37	1.30	1.24
T_6- 56.25% PG+18.75% $CaCl_2$	1.55	1.07	1.34	1.44	1.40	1.33
T_7- 65.62% PG+9.38% $CaCl_2$	1.23	1.25	1.56	1.63	1.41	1.37
Mean	**1.34**	**1.18**	**1.50**	**1.46**	**1.38**	**1.30**
SEm±	0.097	0.148	0.118	0.121	0.114	0.112
CD (P = 0.05)	**NS**	**NS**	**NS**	**NS**	**NS**	**NS**
CV (%)	16.44	18.09	16.12	16.54	16.49	17.29

Table 10. Effect of different levels of PG and $CaCl_2$ on soil ESP after harvest of rice and wheat

Treatment	**2021**		**2022**		**2023**	
***Direct effect* after *kharif* rice**	**0-15 cm**	**15-30 cm**	**0-15 cm**	**15-30 cm**	**0-15 cm**	**15-30 cm**
T_1- Control	19.81	21.43	16.01	19.52	14.98	16.52
T_2- 75% PG	15.01	17.21	11.01	16.16	9.91	12.96
T_3- 75% $CaCl_2$	14.98	15.88	11.18	15.85	10.18	12.63
T_4- 37.5% PG+37.5% $CaCl_2$	14.12	15.23	10.32	14.68	7.85	11.18
T_5- 18.75% PG+56.25% $CaCl_2$	12.99	14.77	9.22	13.31	7.47	10.34
T_6- 56.25% PG+18.75% $CaCl_2$	13.02	14.74	9.16	14.98	7.84	11.13
T_7- 65.62% PG+9.38% $CaCl_2$	13.61	15.04	9.85	15.20	8.35	11.47
Mean	**14.79**	**16.33**	**10.97**	**15.74**	**9.51**	**12.32**
SEm±	0.99	1.12	0.70	1.04	0.58	0.95
CD (P = 0.05)	**2.94**	**3.32**	**2.09**	**3.10**	**1.73**	2.82
CV (%)	13.36	13.70	12.84	13.33	12.21	15.40
Treatment	**2021-22**		**2022-23**		**2023-24**	
***Residual effect* after *rabi* wheat**	**0-15 cm**	**15-30 cm**	**0-15 cm**	**15-30 cm**	**0-15 cm**	**15-30 cm**
T_1- Control	19.09	20.56	17.14	19.04	15.93	17.76
T_2- 75% PG	10.54	13.28	7.33	12.78	6.52	10.84
T_3- 75% $CaCl_2$	11.02	12.89	7.89	12.04	6.64	9.58
T_4- 37.5% PG+37.5% $CaCl_2$	10.00	12.72	7.73	11.72	7.18	10.53
T_5- 18.75% PG+56.25% $CaCl_2$	10.38	11.87	7.87	10.96	6.15	9.89
T_6- 56.25% PG+18.75% $CaCl_2$	9.89	12.90	7.50	12.40	6.91	9.66
T_7- 65.62% PG+9.38% $CaCl_2$	10.06	13.75	7.24	12.50	6.98	10.44
Mean	**11.57**	**14.00**	**8.96**	**13.10**	**8.04**	**11.24**
SEm±	0.84	1.17	0.74	1.00	0.49	0.78
CD (P = 0.05)	**2.49**	**3.48**	**2.20**	**2.96**	**1.44**	**2.33**
CV (%)	14.49	16.73	16.51	15.23	12.08	13.96

Table 11. Economics of different treatments

Treatment	**Rice equivalent yield (kg/ha)**	**Fixed cost (₹/ha)**	**Variable cost (₹/ha)**	**Total cost of cultivation (₹/ha)**	**Gross return (₹/ha)**	**Net return (₹/ha)**
T_1- Control	8064	112596	0	112596	149757	37161
T_2- 75% PG	10499	112596	16238	128834	194961	66127
T_3- 75% $CaCl_2$	10210	112596	70063	182659	189604	6945
T_4- 37.5% PG+37.5% $CaCl_2$	10812	112596	43150	155746	200778	45032
T_5- 18.75% PG+56.25% $CaCl_2$	11339	112596	56607	169203	210574	41372
T_6- 56.25% PG+18.75% $CaCl_2$	11486	112596	29694	142290	213286	70996
T_7- 65.62% PG+9.38% $CaCl_2$	10925	112596	22970	135566	202881	67315

Selling price of rice grain: ₹.18.57/kg; rice straw: ₹.4.5/kg; wheat grain: ₹.26/kg; wheat straw: ₹.2.0/kg; phosphogypsum: ₹.2400/t; $CaCl_2$: ₹.13940/t highest reduction in soil ESP was recorded with treatment (T_3) 75% $CaCl_2$ (9.58 %) but which was comparable to T_2, T_4, T_5, T_6 and T_7 treatments at 15-30 cm soil depth. Maximum soil ESP (20.56, 19.04 and 17.76 %) was recorded under the control treatment where neither PG nor $CaCl_2$ was applied at 15-30 cm soil depth during first, second and third years, respectively.

The reduction in ESP might be due to the partial substitution of PG with $CaCl_2$ enhances the reclamation efficiency due to the higher solubility and faster availability of Ca^{2+} from $CaCl_2$, which promotes more effective Na^+-Ca^{2+} exchange and leaching of sodium salts from the soil exchange complex. The ESP reduction was more prominent in the surface layer (0-15 cm) compared to the subsurface (15-30 cm), which could be attributed to the greater contact of amendments with soil particles and improved percolation and leaching in the upper soil horizons (Qadir *et al*. 2014). Moreover, the residual effects of the applied amendments persisted across the cropping years, as evidenced by the continuing decline in ESP even in the subsequent wheat crop cycles. In line with earlier research by Gharaibeh *et al*. (2009) and Luiz *et al*. (2022), this persistence indicates a long-term ameliorative benefit from the amendments.

3.7 Economics

The data on the economics of various PG and $CaCl_2$ treatments (Table 11) show significant differences across treatments in terms of total cost of production, gross return and net return. Due mainly to variations in the variable cost of the amendments, the total cost of cultivation ranged from ₹ 112596 ha^{-1} (control) to ₹ 182659 ha^{-1} (T_3: 75% $CaCl_2$). Because $CaCl_2$ is more expensive on the market than PG, treatments containing higher quantities of $CaCl_2$ (T_3 and T_5) were more expensive. The gross returns showed the similar pattern as the yield, with T_6 (56.25% PG + 18.75% $CaCl_2$) showing the greatest return (₹ 213286 ha^{-1}), followed by T_5 (₹ 210574 ha^{-1}). The control (T_1) had the lowest gross return (₹ 149757 ha^{-1}).

The net returns ranged from ₹ 6945 ha^{-1} in T_3 (75% $CaCl_2$) to ₹ 70996 ha^{-1} in T_6 (56.25% PG + 18.75% $CaCl_2$). Treatment T_6 recorded the maximum profitability due to a favorable balance between input cost and yield gain. The combined use of gypsum and $CaCl_2$ improved yield and economic returns in saline-sodic soils by enhancing soil structure, leaching excess salts, and promoting better crop establishment. Overall, the partial substitution of PG with a small proportion of $CaCl_2$ (T_6: 56.25% PG + 18.75% $CaCl_2$) proved to be the most economically viable treatment. The results suggest that moderate combinations of PG and $CaCl_2$ are more cost-effective than sole or high-rate applications of $CaCl_2$ which, although effective in improving soil conditions, substantially increase production (Gharaibeh *et al*. 2009 and Ahmed *et al*. 2017).

4. Conclusion

Application of phosphogypsum (PG) and calcium chloride ($CaCl_2$) was found to reclaim saline-sodic soil and was comparable to sole application of PG. The economic feasibility remains on the cost variation caused due to availability of $CaCl_2$ as compared to PG where it is being marketed throughout Gujarat by GNFC, Vadodara. However, reducing the dose up to 18.75% of GR of $CaCl_2$ in combination with 56.25% PG increased the crop yields of rice-wheat and beneficial in reclamation in deeper layers.

Disclaimer (Artificial Intelligence)

Author(s) hereby declare that no generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

Competing Interests

Authors have declared that no competing interests exist.

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