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Efficiency of Phosphogypsum and Mined Gypsum in Reclamation and Productivity of Rice–Wheat Cropping System in Sodic Soil

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In this study, efficacies of mined gypsum and phosphogypsum (PG), when applied at equivalent doses, were compared for sodic soil reclamation and productivity of rice–wheat system. Application of PG, followed by karnal grass as first crop, resulted in the greatest reduction of soil pH and exchangeable sodium percentage (ESP) followed by PG applied at 10 Mg ha⁻¹ alone. Application of PG at 10 Mg ha⁻¹ resulted in greater yields of both rice and wheat than other treatments. Diethylenetriaminepentaacetic acid (DTPA)–extractable micronutrients of PG-treated soil were greater than in mined gypsum–treated soil. A greater portion of applied P entered the calcium (Ca)–phosphorus (P) fraction in PG-treated soil, which also resulted in more soluble P than the mined gypsum–treated soil. Phosphogypsum effected greater increase in aggregation, soil organic carbon, microbial biomass carbon, and aggregate associated carbon and decrease in zeta potential, leading to increased hydraulic conductivity and moisture retention capacity in soil over mined gypsum–treated soil.

Keywords Aggregate, exchangeable sodium, micronutrients, P fraction, phosphogypsum, sodic soil, zeta potential

Introduction

Land degradation is a major factor constraining world food production, and sodification is a large component of that degradation. Sodic soils are characterized by the occurrence of excess sodium (Na⁺) to levels that can adversely affect soil structure and disturb availability of some nutrients to plants. Such changes ultimately affect crop growth and yield. There are large areas of the world that exist under sodic soils and need attention for efficient, inexpensive, and environmentally feasible amelioration. Phosphogypsum (PG), the by-product of wet acid production of phosphoric acid from rock phosphate, contains more than 92% calcium sulfate and should be an excellent source of calcium, which may be used as a soil conditioner for sodic, solonets, and solonchic soils. Phosphogypsum is produced by the phosphate fertilizer industry and emanates from the production of phosphoric acid

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from rock phosphate through a wet process. In the wet process, production of 1 ton of phosphoric acid causes the formation of 4.5 to 5.5 tons of PG. Phosphogypsum consists primarily of calcium sulfate dihydrate ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) with small amounts of silica, usually as quartz and unreacted phosphate rock.

In the late 1980s, the agricultural use of PG was suspended by the U.S. Environmental Protection Agency when the agency reduced the level of allowable radioactive radium-226 and associated radon in PG by a factor of five. This restriction put some of the PG into the nonallowable category and therefore made PG illegal for agricultural use (U.S. Gypsum Company 1990). Since then, the U.S. Environmental Protection Agency has permitted the controlled use of PG in agriculture. To prevent environmental and health risks, the commercial use of PG in agriculture is permitted in the USA if the certified average ^{226}Ra concentration does not exceed 370 Bq kg^{-1} (U.S. Environmental Protection Agency 1992). The atomic energy regulation board (AERB), India, has been examining the radiological safety implications of use of PG in agriculture. Based on the principles followed internationally, the board in recent guidelines decided that there is no restriction for the use of PG in agricultural application from the radiological safety consideration (AERB Newsletter 2008). Additionally, using PG as an amendment in agricultural soils may dilute its pollutants, such as fluoride, heavy metals, and radionuclides.

In India about 11 million tons of PG is generated per year, creating huge stockpiles at plant sites. There is public concern about the safety of these disposals and the need to restore the environment where these products are accumulated. In India, mined gypsum had been used as an amendment in the amelioration of saline and sodic lands for the agricultural use because it has the ability to diminish Na saturation of the soil. Reclamation of sodic soils for agricultural use involves the use of calcium (Ca) amendments to reduce Na saturation. Phosphogypsum contains a high proportion of $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$, an efficient amendment that has been widely used in the saline-sodic marsh soils from southwestern Spain (Dominguez *et al.* 2001).

India has 6.73 m ha of salt-affected soils, of which 3.77 m ha is sodic soil (Sharma, Rao, and Saxena 2004). The diminishing stock of mined gypsum and a vast pillage of PG in India, necessitated exploring the possibilities of its use as an amendment of sodic soils, which could contribute to the elimination of this waste from the plant sites. It may be a valuable resource for farmers for reclaiming sodic soil, and as an added bonus, it contains calcium, sulfur (S), and phosphorus (P), which are also readily available to growing plants. Therefore, the present study was conducted to compare the efficiency of PG and mined gypsum, when applied at chemically equivalent rates in (i) reclaiming highly sodic soil; (ii) increasing P fractions, available P, and micronutrient content of soil; (iii) improving the physical properties of soil; and (iv) enhancing the productivity of the rice-wheat system.

Material and Methods

Experimental Site

The experimental site was located at $26^\circ 47' 58''$ N latitude and $80^\circ 46' 24''$ E longitude in the salt-affected soils of the central Indo-Gangetic plain. The area represent a semi-arid subtropical climate characterized by hot summer and a cool winter, with mean annual rainfall of 880 mm, most of which occurs during June to September. The soil is fine, loamy, mixed hyperthermic and can be classified as Typic Natraustalf (Soil Survey Staff 1998). The soil had a sandy clay loam texture with the following parameters: sand 490 g kg^{-1} , silt

185 g kg⁻¹, clay 325 g kg⁻¹, pH 9.8, electrical conductivity (EC_e) 1.9 dSm⁻¹, exchangeable sodium percentage (ESP) 38.5, calcium carbonate (CaCO₃) 20.8 g kg⁻¹, organic carbon 0.30 g kg⁻¹, and cation exchangeable capacity (CEC) 16.7 cmol (p⁺) kg⁻¹. Initial values for Olsen P, diethylenetriaminepentaacetic acid (DTPA)–extractable zinc (Zn), iron (Fe), manganese (Mn), and copper (Cu) were 18.87, 0.64, 5.5, 5.3, and 1.08 mg kg⁻¹, respectively. Gypsum requirement (GR) of soil was determined according to the methods of U.S. Salinity Laboratory Staff (1954) and used for calculation of equivalent doses of PG. Chemical analysis data for the PG and the mined gypsum are given in Table 1. Because of the radioactivity concerns of the PG, radionuclides [viz. ²²⁶radium (²²⁶Ra), ²³²thorium (²³²Th), ²³⁸uranium (²³⁸U), and ⁴⁰potassium (⁴⁰K)], were analyzed in PG by γ spectrometry at the Bhabha Atomic Research Centre (BARC), Trombay, Mumbai.

Field Experimental Design

Six treatments were laid out in plots of 40 m² in a randomized block design with four replications. Treatments were T₁, 50 GR_M (mined gypsum applied at 50% GR, i.e., 10.5 Mg ha⁻¹); T₂, 50 GR_{PG} [PG applied at 10 Mg ha⁻¹ (equivalent to 50 GR_M)]; T₃, 50 GR_{PG}–KFC [PG applied at 10 Mg ha⁻¹, followed by karnal grass (*Dicanthium fusca* L. Kunth) as first crop]; T₄, 25 GR_M + 25 GR_{PG} (mined gypsum applied at 5.25 Mg ha⁻¹ and PG applied at 5 Mg ha⁻¹); T₅, 25 GR_{PG} (PG applied at 5 Mg ha⁻¹); and T₆, 12.5 GR_M + 12.5 GR_{PG} (mined gypsum applied at 2.62 Mg ha⁻¹ and PG applied at 2.5 Mg ha⁻¹). Rice followed by wheat was taken in all the treatments except T₃, where karnal grass was used as the first crop instead of rice during the first year, to explore the possibility of taking the nonfood crop immediately after reclamation using PG.

The plots were plowed to fine tilth, and PG and mined gypsum were applied followed by 8-cm irrigations to all plots, allowing for vertical leaching. The irrigation water had

Table 1
Chemical composition of phosphogypsum and mined gypsum

Element	Phosphogypsum	Mined gypsum
S (%)	16.4	16.1
Ca (%)	18.9	18.3
Si (%)	3.35	0.82
P (%)	0.34	0.01
Mg (%)	0.01	0.04
Na (%)	0.11	0.18
K (%)	0.22	0.24
Al (%)	0.02	0.06
Fe (%)	0.30	0.01
Cu (%)	0.09	—
Zn (%)	0.15	—
Mn (%)	0.05	—
⁴⁰ K (Bq kg ⁻¹)	ND	302 ± 25
²³⁸ U (Bq kg ⁻¹)	3370 ± 32	21 ± 2
²³² Th (Bq kg ⁻¹)	23 ± 6	25 ± 2
²²⁶ Ra (Bq kg ⁻¹)	1895 ± 39	39 ± 4

pH 7.7, EC 0.87 dS m⁻¹, residual sodium carbonate (RSC) 1.0 mmol L⁻¹, and sodium absorption ratio (SAR) 1.16. After 7 days, CSR23 rice (*Oryza sativa* L.) was transplanted in all the experimental plots except T₃, at row-to-row spacing of 20 cm and hill-to-hill distance of 15 cm. In T₃, during the first year of experimentation (2006–2007), two suckers of karnal grass were transplanted at row-to-row spacing of 20 cm and hill-to-hill distance of 15 cm, and rice was transplanted for the next two seasons (2007–2008 and 2008–2009). A basal application of half of total nitrogen (N; i.e., 75 kg N ha⁻¹) and full dose of P at 60 kg P₂O₅ ha⁻¹ were applied at the time of puddling. The rest of N was applied in two equal splits at tillering and panicle initiation. Irrigation water (8 cm) was applied after 3 days of the disappearance of the ponding water. At maturity the crop was harvested manually, sun dried for 5 days, and threshed to record grain yield, which was reported on 14% moisture basis in terms of Mg ha⁻¹. The layout of the experimental field was not disturbed for the subsequent wheat crop (KRL19). Fertilizer (N/P₂O₅ = 60:60 kg ha⁻¹) was applied as basal dose to all the plots. The rest of N (i.e., 60 kg N ha⁻¹) was applied in two equal splits at the first and second irrigations. The mature wheat crop was harvested from the entire plot, and after sun drying, the harvested material was threshed to record grain yield.

Soil Analysis

The soil samples from 0–15 cm deep were taken at harvesting of rice and wheat after completion of the experiment, air dried, and ground to pass through a 2-mm screen. The pH, EC, and ESP were measured in soil saturation extract as per U.S. Salinity Laboratory Staff (1954) and P was determined by Olsen's method (Olsen et al. 1954). The DTPA-extractable micronutrients, Zn, Fe, Mn, and Cu, were determined as per the procedure outlined by Lindsay and Norvell (1978). Sequential chemical extraction for inorganic P was carried out using 1 M ammonium chloride (NH₄Cl), a reaction time of 30 min for soluble P; 0.5 M ammonium fluoride (NH₄F), reaction time 1 h for aluminum (Al) P; 0.1 M sodium hydroxide (NaOH), reaction time 17 h for Fe-P; 0.3 M sodium citrate (Na₃C₆H₅O₇), 1 M sodium bicarbonate (NaHCO₃), and 1 g sodium thiosulfate (Na₂S₂O₄) with reaction time of 15 min in a water bath at 85 °C for reductant soluble P; and 0.25 M sulfuric acid (H₂SO₄) with reaction time 1 h for Ca-P (Olsen and Sommer 1982). A similar process was followed for fractionation of P in the initial soil.

The MBC was determined according to the trichloromethane (CHCl₃) fumigation–extraction method in field-moist samples (Vance, Brookes, and Jenkinson 1987). Fumigated and unfumigated samples were incubated for 24 h at 25 °C at constant moisture content. Microbial carbon (C) was extracted from both fumigated and nonfumigated samples with 0.5 M potassium sulfate (K₂SO₄) and digested in the presence of potassium persulfate (K₂S₂O₈) and 0.025 M sulfuric acid (H₂SO₄) in a digestion block at 120 °C for 2 h. The amount of carbon dioxide (CO₂) C thus evolved was estimated by following the method of Snyder and Trofymow (1984). Microbial C was calculated by subtracting the extracted C in unfumigated samples from that measured in fumigated samples and dividing it by a Kc value of 0.45 (Joergensen 1996).

The soil samples collected after the third-year rice and wheat crops were analyzed for physical properties. The amount of mechanically dispersed clay and the zeta potential (ζ potential) of the clay particles from the soils of differently treated plots were determined according to the procedures of Chorom and Rengasamy (1995). The samples of air-dried soils were sieved and 2- to 4-mm size aggregates were collected. Three replicates of 50 g of aggregates were wet sieved for 5 min on a set of three sieves of 1000-, 500-,

and 250- μm diameters. The weight of each aggregate fractions was recorded after drying at 105 °C for 24 h. The wet aggregate stability results were determined and expressed as mean weight diameter (MWD, Kemper and Rosenau 1986). Undisturbed soil cores of 10-cm soil columns were collected from all the plots in 7.5-cm-diameter and 15-cm-high core samplers. The saturated hydraulic conductivity (HC) was determined by maintaining a constant head (3 cm) of water above the soil surface, and water percolation was measured (Greene et al. 1988). Organic carbon in bulk soil and associated with different aggregate size fractions was determined by wet digestion with potassium dichromate along with 3:2 H_2SO_4 /85% phosphoric acid (H_3PO_4) digestion mixture in a digestion block set at 120 °C for 2 h (Snyder and Trofymow 1984).

Statistical Analysis

The statistical analysis was done by using the procedure described by Gomez and Gomez (1983). The variance analyses were performed on 5% probability level, and least significant difference (LSD) tests were used to determine the difference among the treatments.

Results and Discussion

Rice and Wheat Yield

The yield data on rice and wheat expressed as equivalent yield of rice, influenced by the application of PG in the sodic soil, is presented in Figure 1. Application of PG at 10 Mg ha^{-1} resulted greater yield (4.5 Mg ha^{-1}) of rice over the treatment 50 GR_M (4.22 Mg ha^{-1}) and 25 GR_M + 25 GR_PG (4.32 Mg ha^{-1}) in the first year of reclamation. Similarly, application of PG at 5 Mg ha^{-1} resulted comparatively greater yield than 12.5 GR_M + 12.5 GR_PG . The treatment with karnal grass yielded lowest equivalent yield of rice because of its low market price. The yield of followup wheat (*Triticum aestivum* L.) resulted in a similar increase in the PG-treated fields as recorded in rice; however, the greatest yield (3.47 Mg ha^{-1}) was recorded in T_3 where the karnal grass was taken as first crop instead of rice. The absolute yield of rice and wheat increased in all the reclamation treatments in the subsequent year. However, the yield gap among 25 GR_PG , 50 GR_PG , and 50 GR_M narrowed with every passing growing season. The decreasing yield gap of rice and wheat applied with gypsum at 50 GR has earlier been reported by Singh et al. (2004). The rice–wheat cropping system is common and characteristic of the salt-affected areas; thus the wheat crop, sown after rice, often yields good results because of heavy salt leaching from the root zone during rice. The high grain yield under PG can be the result of rich Ca availability in PG as compared to mined gypsum, which replaces the exchangeable Na from the soil exchange complex. These results are in conformity with those of Kumar and Abrol (1984), who reported that growing karnal grass as the first crop after reclamation results in greater subsequent crop yields.

Amendment Effect on Soil pH and ESP

Application of PG at 10 Mg ha^{-1} , followed by karnal grass (*Leptochloa fusca* L. Kunth) as the first crop, resulted the greatest reduction of soil pH followed by PG applied at 10 Mg ha^{-1} (Table 2). The PG treatment decreased soil pH by increasing the amount of Ca^{2+} present in the soil solution and increasing H^+ ion due to residual sulfuric acids. The ESP

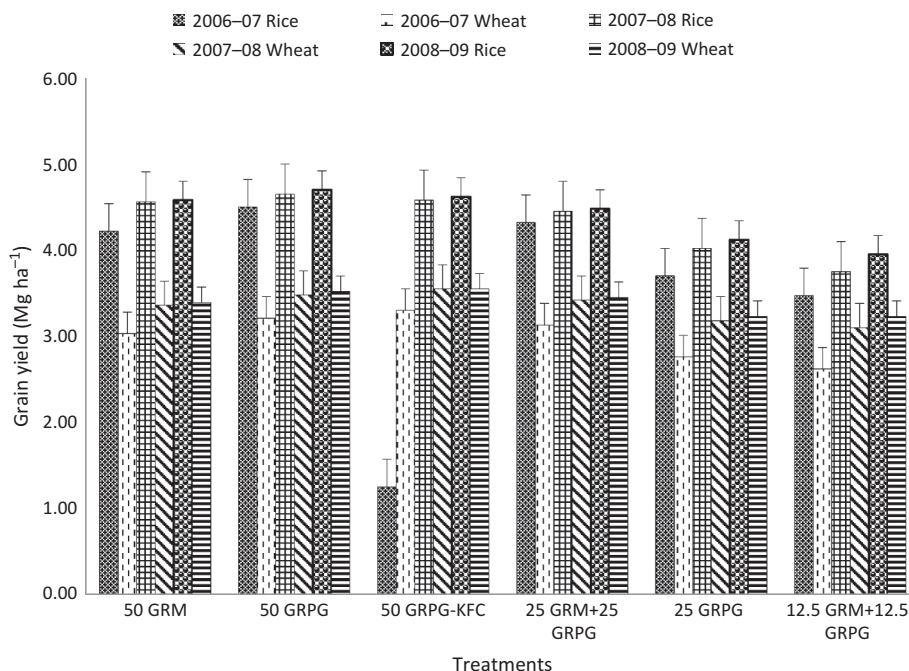


Figure 1. Effects of phosphogypsum on the grain yield of rice and wheat. Bars represent the LSD value at $P = 0.05$. GR_M, gypsum requirement as mined gypsum; GR_{PG}, gypsum requirement as phosphogypsum equivalent to mined gypsum; and KFC, Karnal grass (first crop in place of rice).

of soil showed a similar trend as pH (Table 2). The PG treatment resulted in greater reduction of pH and ESP because of its greater solubility over mined gypsum; Ca^{2+} permeates to lower depths because of the increased rate of water entry and causes reduction in ESP even at a greater depth. The effectiveness of karnal grass in greater reduction is because it has an extensive root system that increases the partial pressure of CO_2 (P_{CO_2}), enhancing the dissolution of calcite (Qadir et al. 2006), which reduces the sodicity of calcareous sodic soil.

Olsen P and P Fractions

Application of PG resulted in greater available P than in mined gypsum-treated plots (Table 2). The P enrichment was enhanced in PG-treated plots by the application of P fertilizer to rice and wheat crop and residual P in PG. The increase in CO_2 concentration from underground biomass decomposition and greater decrease in pH resulted in an increase in available P in amended soils. In the initial soil, the fractional composition of the mineral phosphates was dominated by calcium phosphates and was greater than that of aluminum and iron phosphates taken together (Table 3). Formation of sodic soil accompanied by alkalization of the soil solution, resulted in a considerable rise in calcium phosphates and decrease in available P. Application of PG to the sodic soil resulted in a considerable increase in the contents of soluble P, calcium P, and Fe P over the initial soil and soil treated with mined gypsum. This is probably due to the additional supply of P from PG, which is confirmed by the rise in the total P. As the pH of the soil solution was alkaline, a greater fraction of applied fertilizer P and/or P contained in PG precipitated as Ca-P in the

Table 2
Effects of reclamation treatment on soil chemical properties

Treatment	pH	EC _e (dS m ⁻¹)	ESP	P (mg kg ⁻¹)	Zn (mg kg ⁻¹)	Fe (mg kg ⁻¹)	Mn (mg kg ⁻¹)	Cu (mg kg ⁻¹)
50 GR _M	8.6	0.9	20.4	19.25	0.78	9.50	10.12	2.16
50 GR _{PG}	8.5	0.8	18.3	24.57	1.00	11.10	11.14	2.73
50 GR _{PG} – KFC	8.4	0.7	17.8	25.45	0.96	9.82	9.24	2.50
25 GR _M + 25 GR _{PG}	8.5	0.8	19.4	19.81	0.85	9.68	8.18	2.13
25 GR _{PG}	8.7	0.6	25.2	18.70	0.70	7.88	5.52	2.00
12.5 GR _M + 12.5 GR _{PG}	8.9	0.6	26.5	17.45	0.62	5.56	5.20	1.17
LSD (<i>P</i> = 0.05)	0.1	0.1	1.5	2.45	0.15	0.84	1.18	0.13

Table 3
Sequential chemical extraction of inorganic P (mg kg⁻¹) in reclaimed soils

Treatments	Soluble P	Fe P	Al P	Reductant soluble P	Ca P	Total inorganic P ^a
50 GR _M	11.43	22.48	8.96	12.65	109.35	164.87
50 GR _{PG}	15.23	24.92	9.58	14.87	115.35	179.95
50 GR _{PG} – KFC	16.5	23.52	10.02	13.19	114.56	177.79
25 GR _M + 25 GR _{PG}	12.45	23.28	8.5	14.18	110.5	168.91
25 GR _{PG}	10.56	18.34	8.6	16.68	109.6	163.78
12.5 GR _M + 12.5 GR _{PG}	9.86	16.35	8.24	17.85	108.62	160.92
Initial	8.56	13.23	7.59	18.39	95.18	142.95
LSD (<i>P</i> = 0.05)	1.12	1.22	0.88	2.8	2.8	5.2

^aSum of all fractions.

amended soils, a small fraction of P entered in to Fe-P. Hartikainen (1989) suggested that initial P sorption in soils occurred by reaction with Fe hydroxides as the Fe-P bond is more stable than Al-P bond. In our study we found that the reductant soluble P, which represents a fairly stable form of soil P encapsulated by Fe oxides and Al-P, were at par in soil treated with PG and mined gypsum. However, Al-P content decreased and reductant soluble-P content increased at lower dose of amendments. The total P contents in both 50 GR_{PG} and 50 GR_{PG}-KFC were at par while the available P was statistically greater in the latter than the former. The increase in total P in mined gypsum-treated soil over the initial soil may be due to application of P fertilizer to both rice and wheat crops.

DTPA-Extractable Metal

The DTPA-extractable Fe, Cu, Zn, and Mn contents increased significantly as a result of the application of mined gypsum and PG, and the latter treatment resulted in more soil-test values than the former (Table 2). The fractions of metals retained in available form differ as a function of pH reduction due to the treatments. The greater micronutrient content in PG treated soil may be attributed to greater reduction of pH over mined gypsum-treated soil and addition of extra micronutrients contained in PG. Application of amendments at greater dose resulted in greater availability of micronutrients than at a lower dose. Sodic soils usually have poor availability of most micronutrients, which is generally attributed to high soil pH (Page, Chang, and Adriano 1990; Naidu and Rengasamy 1993). Generally, the solubility of cationic trace elements decreases with increasing pH (Page, Chang, and Adriano 1990). Micronutrient availability in sodic soils is further affected by the nature of constituent minerals (i.e., presence of carbonate minerals such as calcite), which act as active sorption sites for the precipitation of several trace elements (Chen and Barak 1982). Therefore, in sodic soils, the solubility of micronutrients such as copper (Cu), Fe, manganese (Mn), and Zn is particularly low (Curtin and Naidu 1998).

Physical Properties

The decrease in ζ potential of the soil clays was much lower in the PG-treated soil than the others (Table 4). Planting karnal grass along with PG (50 GR_{PG}-KFC) slightly decreased the ζ potential over the 50 GR_{PG} + 50 GR_M. The mechanisms of decrease in ζ potential

Table 4
Effects of reclamation treatment on change in soil physical properties of surface soil after 3 years of rice–wheat cropping

Treatment	ζ potential (-mv)	Dispersible clay ^a	Available water (kg kg ⁻¹)	Bulk density (Mg m ⁻³)	MWD (mm)	Ks (cm h ⁻¹)
50 GR _M	18.41	20.89	0.201	1.40	0.474	0.246
50 GR _{PG}	17.19	18.35	0.209	1.35	0.562	0.324
50 GR _{PG} – KFC	16.88	17.53	0.219	1.35	0.586	0.369
25 GR _M + 25 GR _{PG}	17.76	19.86	0.194	1.39	0.529	0.304
25 GR _{PG}	28.89	27.24	0.119	1.43	0.424	0.176
12.5 GR _M + 12.5 GR _{PG}	29.53	28.92	0.109	1.44	0.403	0.168
LSD (<i>P</i> = 0.05)	1.53	1.82	0.010	0.05	0.063	0.076

^aPercentage of total clay.

are reduction in the ESP and increase in the concentration of Ca^{2+} . These are responsible for flocculation of soil clays and particularly Ca^{2+} for their aggregation (Chorom and Rengasamy 1997).

Dispersible clay content expressed as percentage of total clays was significantly reduced in the PG-treated soil (Table 4). There was no significant difference of the dispersible clays among the 25 GR_{PG} and 12.5 GR_{M} + 12.5 GR_{PG} treatments. The result clearly shows that PG application can result in greater reduction of ESP and dispersible clays at greater dose (i.e., 50 GR_{PG}).

Application of PG to sodic soil resulted in the formation of agronomically favorable soil structure and moisture-retention capacity. Water-stable aggregates expressed as MWD were increased more significantly by application of PG than mined gypsum (Table 4). Greater decreases in soil ESP and pH and faster release of Ca^{2+} from the dissolution of PG enabled better stabilization of clay than mined gypsum. Application of PG followed by karnal grass as a first crop still result in better water-stable aggregates as a result of the binding effects of its extensive root system.

Saturated hydraulic conductivity (Ks) was more significantly increased by application of PG than by mined gypsum (Table 4). Because of its crystalline structure and faster rate of dissolution, PG creates a more porous soil matrix and increased permeability. Because of its relatively high solubility, PG subsequently releases Ca^{2+} and SO_4^{2-} that can be leached through the plow layer to benefit the physicochemical properties of both topsoil and subsoil horizons (Pavan, Bingham, and Pratt 1982; Farina and Channon 1988; Carvalho and van Raij 1997). Keren and Shainberg (1981), in a simulated rain (27 mm h^{-1}) experiment on a sodic soil, found that PG at 3.4 to 6.8 t ha^{-1} maintained a much greater infiltration rate than did mined gypsum. Application of PG at 10 Mg ha^{-1} , followed by karnal grass as the first crop, resulted in the greatest Ks value of 0.369 cm h^{-1} . This may be because karnal grass has an extensive root system, which can penetrate to a soil depth of 1 m (Malik, Aslam, and Naqvi 1986), creating root channels that facilitate entry of water in to soil at faster rate. Similarly the greater value of available water and lower value of bulk density was recorded when the PG was applied at 10 Mg ha^{-1} followed by karnal grass as first crop or alone.

Soil Organic Carbon, MBC, and Aggregate-Associated Carbon

Under sodic soil, native SOM is rapidly lost as its solubility, decomposability, and accessibility increases. Concurrently, C inputs into the soil are decreased as sodicity causes plant health to decline as a result of adverse soil physical and chemical conditions (Wong *et al.* 2006). The application of PG and mined gypsum increased the soil organic carbon (SOC) in surface soil. The SOC in the treatments 50 GR_{M} , 50 GR_{PG} , 50 GR_{PG} -KFC, and 25 GR_{M} + 25 GR_{PG} were at par and significantly greater over the initial soil and over the treatments with low levels of amendments, that is, 25 GR_{PG} and 12.5 GR_{M} + 12.5 GR_{PG} . The soil MBC content was greatest (0.94 $\mu\text{g g}^{-1}$) in the treatment 50 GR_{PG} -KFC and lowest (0.65 $\mu\text{g g}^{-1}$) in 25 GR_{PG} (Table 5). Batra and Manna (1997) found that MBC as percentage of total organic C tended to increase with decrease in soil pH. Aggregate-associated C was greatest in the size fraction of 0.5–1 mm and lowest in <0.5 mm. Loss of soil organic C in sodic soil takes place because of the alkaline hydrolysis of organic matter, surface runoff, and leaching of dissolved organic C. The Ca^{2+} from the PG and/or mined gypsum prevent this loss by (i) forming a cation bridge of Ca^{2+} with organic C and (ii) improving the soil aggregate formation and increasing aggregate-associated C. Dispersion of aggregates, often with cores containing organic material caused by sodicity, also increases

Table 5
Effects of reclamation treatment on change in soil carbon

Treatments	Total SOC in bulk soil (g kg ⁻¹)	MBC in bulk soil (μg g ⁻¹)	Aggregate-associated C (g kg ⁻¹)		
			1–2 mm	0.5–1 mm	<0.5 mm
50 GR _M	2.36	0.89	3.95	4.9	2.45
50 GR _{PG}	2.59	0.90	4.15	5.6	3.07
50 GR _{PG} – KFC	2.86	0.94	4.5	5.9	3.03
25 GR _M + 25 GR _{PG}	2.46	0.90	4.2	5.7	2.61
25 GR _{PG}	1.58	0.65	2.89	3.15	1.62
12.5 GR _M + 12.5 GR _{PG}	1.50	0.69	2.68	3.0	1.61
LSD (<i>P</i> = 0.05)	0.52	0.22	0.60	0.93	0.50

the availability of C, resulting in an increase in its accessibility and degradability for the microbial population (Tisdall and Oades 1982).

Conclusions

Phosphogypsum was found to be better at reclaiming materials than mined gypsum. Application of PG results in a greater decrease in surface soil pH and ESP, resulting in a greater yield of rice and wheat over the equivalent dose of mined gypsum. The contents of soluble P, calcium P, and Fe-P were greater in PG-treated soil than the initial soil and mined gypsum-amended soil. A greater fraction of applied fertilizer P and/or P contained in PG precipitated as Ca-P in the PG-amended soils, and a small fraction of P entered into Fe-P. Besides this, application of PG resulted in an increase in available P and micronutrients such as Fe, Cu, Zn, and Mn in soil over the equivalent amount of mined gypsum. Phosphogypsum effected an increase in aggregation, soil organic carbon, MBC, and aggregate-associated carbon, leading to increased hydraulic conductivity and moisture retention capacity in soil over mined gypsum-treated soil. Sodic soil reclamation may provide an alternate sink for PG disposal with additional value to farmers.

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