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Can conjunctive use of gypsum, city waste composts and marginal quality water rehabilitate saline-sodic soils?

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ABSTRACT

Soil sodicity is major stress limiting crop production in the arid and semi-arid regions where groundwater contains excess salts with variable sodium adsorption ratio (SAR). This study investigated the impact of farmyard manure (F) and city compost in conjunction with gypsum to rehabilitate saline-sodic soil having $pH_{1:2}$ (10.7), electrical conductivity ($EC_{1:2}$; 3.09 dS m^{-1}) and exchangeable sodium (70.3 %). Soil amended with gypsum (25 and 50 % of gypsum requirement, GR) and/or with 10 t ha^{-1} F (GR25 F), Karnal (GR25 K) and Delhi compost (GR25D) were incubated at moisture ~60 % maximum WHC. One month incubated soils were sequentially leached up to ten pore volumes using saline water of SAR 5 and 15 with constant EC (6 dS m^{-1}). The increment in SAR of applied water reduced the cumulative loss of Ca^{2+}, Mg^{2+}, and K^+ and increased the release of Na^+. Application of amendments and intense leaching decreased the soil pH_s, EC_e and alkalinity. Leaching with SAR 5 water decreased SAR of soil saturation extract to 9.7 compared with SAR 15 (17.2). Gapon's selectivity coefficient (K_G) pointed to the greater (0.017) adsorption preference of Ca^{2+} and Mg^{2+} in the soil leached with SAR 15 than SAR 5 (0.014) water. Reclamation depends on inherent soil ESP and supply of Ca^{2+} for exchange phase; $K_G$becomes more prioritized when SAR 15 water applied for leaching. Therefore, conjunctive use of gypsum (GR25) with compost is as effective as gypsum (GR50) on decrement of soil pHs and leaching of soluble salts.

1. Introduction

Soil organic matter (SOM) is an important component of soil that strongly influences the soil physical properties; decomposition and mineralization of SOM recycle nutrients; and quantity and forms of SOM regulate the biological liveliness of soil (Murphy, 2015). Application of organic materials also accelerates the leaching of Na^+, reduces ESP, electrical conductivity (EC), and improves the water-holding capacity and aggregate stability of soil (Chaganti et al., 2015; Singh et al., 2018a). The organic amendments also increased the cation exchange capacity (CEC) and Ca^{2+}, Mg^{2+} and K^+ saturation of the exchange sites of soil (Walker and Bernal, 2008), besides, reducing harmful effects of poor quality irrigation water because of mobilization of native soil Ca^{2+} from $CaCO_3$ and other Ca bearing minerals (Minhas et al., 1995; Choudhary et al., 2011). Conjoint application of organic amendments with gypsum has shown superiority in sodic soil reclamation over the sole application of organic or mineral gypsum (Singh et al., 2018b). In a study, sole application of cattle manure had no significant effect on soil EC or sodium absorption ratio (SAR) in a mesic *Aridic Paleustoll* (Turner et al., 2010) whereas, gypsum-enhanced-compost significantly reduced ESP, exchangeable Mg, and exchangeable cation ratio, enhanced exchangeable calcium per cent, and increased the soil saturated hydraulic conductivity (Bennett et al., 2015). Adding of gypsum and farmyard manure and Ca^{2+} rich compost is also helpful in reducing the harmful effects of marginal quality water rich with Na^+ as it promotes activity of additional Ca^{2+} by dissolution of $CaCO_3$ and other Ca-bearing native minerals (Choudhary et al., 2011). City compost is a valuable source of organic matter rich in several beneficial nutrients (Sundha et al., 2018; Grey and Henry, 1999; Ghosh et al., 2010; Singh et al., 2018a, b). Over the past few years, urban solid waste handling has become a major organizational, financial and environmental challenge in India. Rapid urbanization and changing lifestyles have led to producing nearly 150,000 tonnes of total solid waste per day Anonymous, 2019). Composted urban solid waste, readily

Abbreviations: SAR_e, sodium adsorption ratio of aqueous soil saturation paste extract; pH_s, pH of aqueous soil saturation paste; EC_e, electrical conductivity of aqueous soil saturation paste extract; ESP, exchangeable sodium percent; GR, gypsum requirement; F, farmyard manure; K, Karnal compost; D, Delhi compost; K_G, Gapon's selectivity coefficient; CROSS, cation ratio of soil structural stability; pH_{Le}, leachates pH index; EC_{Le}, leachates EC index; PCA, principal components analysis

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available at a low price, has the potential to lessen the dependency on mineral gypsum as well as a decrease in reclamation cost of saline-sodic soil (Sundha et al., 2018).

Salinity and sodicity induced land degradation is geo-genic with regional presence under predominant arid and semi-arid ecology. The long history of poor quality irrigation and impaired drainage network also aggravate such degradation (Singh, 1998; Ranjbar and Jalali, 2011; Singh et al., 2018a). Soil moisture management in semi-arid and arid areas is faced with limited and unreliable rainfall with high variability in rainfall pattern (Kipkorir, 2002). Further, rainfalls often fail to meet the demand of leaching and aggravate amassing salts in the root zone (Jalali and Merrikhpour, 2008). This problem is likely to further aggravate with expected climate change; especially an increase in temperature and changing pattern of rainfall. The increase in temperature will raise evapotranspiration (ET) requirement of the crops and thus more salt-load in arid and semi-arid regions. Therefore, threatening the ecological and economic resilience of farm productivity and agriculture in these regions. Saline-sodic soil is either non-productive or much less productive as these have poor physical conditions because of greater clay dispersion, poor soil structure, compactness, and limited pore space, impaired hydraulic conductivity, and restricted entry of water and air (Ahmad et al., 2016). High alkalinity, the toxic appearance of Na, and precipitation of $CaCO_3$ further deteriorate the problem of Na induced toxicity and nutritional deficiency in these soils (Chhabra, 1996).

Rehabilitation of saline-sodic soils has a huge potential to increase productivity and improve the livelihood of the inhabitant of salt-affected soil. Supplementing Ca in the form of mineral gypsum is the most common amendment to reclaim sodic soil because of ease in its handling and availability in many countries (Chaganti et al., 2015; Choudhary et al., 2011; Bennett et al., 2015). Before rehabilitation, sodic and saline-sodic soils often suffer from high sodium saturation on exchange sites. The success of reclamation also depend on the quality and availability of irrigation. The aptness of water for reclamation depends on the quantity and quality of electrolytes (Quirk and Schofield, 1955). Application of electrolyte solution or by adding gypsum/external Ca to the irrigation is a possible choice to offset ESP and preserve the permeability of sodic soil. Further, developing a leaching fraction to move Na based salts and excess salts applied below the root zone results in a more efficient ameliorative process. The lack of desirable electrolytes in irrigation water during reclamation is responsible for clay swelling, aggregate disaggregation, and deflocculation; thus, soil permeability loss and impeded drainage (Bennett et al., 2019; Dang et al., 2018). Therefore, the threshold electrolytes concentration (C_{TH}) was proposed for considering reclamation of saline-sodic soil (Quirk and Schofield, 1955; Zhu et al., 2019). To meet the crop water demand under the limited canal water supply and/or insufficient rainfall during the crop cycle, soils of sodicity affected areas are often irrigated with available marginal quality groundwater *viz.*, saline, sodic or variable SAR water (Minhas et al., 1995; Bennett et al., 2015; Zhu et al., 2019). Moreover, fresh canal water is sometimes undesirable because of the rapid dilution of pore systems and overcoming the threshold electrolyte concentration resulting in rapid soil swelling, disaggregation, dispersion, increase in thickness of diffuse double layer and low hydraulic conductivity (Bennett et al., 2019; Dang et al., 2018). The outcome of the soil-water interaction also depends on the proportion of the cation contained in the solute because of varied hydrated ionic radii and electrostatic interactions. In Ca dominated system, structural stability is retained even after reduction in electrolyte concentration because of maintaining minimum spacing condition between clay micelle required for stable aggregation (Quirk and Schofield, 1955). However, adding Na into the system result in sufficient change in energy to overcome the inter-micelle attractive forces, which is affected by the variations in osmotic pressure and characterized by swelling in the clay domain beyond the potential minima (Quirk, 2001). The net dispersive effect of the Na is moderated by the presence of carbonates (Oster et al., 1999; Shainberg and Letey, 1984), oxides (Deshpande et al., 1964), and organic matter (Nelson and Oades, 1998). Adding organic materials to soils is an effective way to increase SOM levels and aggregate stability and other functional soil properties like porosity, soil structure, bulk density, water-holding capacity and pH buffering capacity (Murphy, 2015). Results are complicated and much depends on the nature and content of the organic materials added (Murphy, 2015; Goldberg et al., 1990). In this background, we hypothesized that the conjunctive use of city composts with gypsum could offset the impact of the poor quality water and reduce the amount of gypsum required for reclaiming the sodic soil. Therefore, this laboratory study was accomplished to compare and evaluate the reclamation potential of city composts, farmyard manure with mineral gypsum supplemented with 25 % gypsum requirement (25GR) in an extremely saline-sodic soil leached with marginal quality water of different SAR with similar electrolyte concentration; and, to work out the changes in soil solution and exchange phase and ionic distribution of saline-sodic soil during the reclamation process.

2. Materials and methods

2.1. Soil sampling and amendments

Uncultivated saline-sodic soil (0 – 15 cm) was collected in bulk from *Saraswati* range, Kaithal, Haryana, India (36°43´16˝N, 52°48´48˝E). The soil was air-dried, sieved through 2-mm mesh, thoroughly mixed, homogenized and analyzed. The initial soil had pH of aqueous soil saturation paste 10.16 (pH_s) (whereas $pH_{1:2}$ 10.71), electrical conductivity of aqueous soil saturation paste extract (EC_e) was 12.15 dS m^{-1} (whereas, $EC_{1:2}$ 3.09 dS m^{-1}) and 77.5 % of exchangeable sodium percent (ESP). Texturally, the soil was loam and contained 0.14 % organic C, 1.45 % $CaCO_3$, and 59.3, 17.4 and 23.3 % of sand, silt and clay, respectively. The gypsum requirement for 100 percent neutralization (GR100) of sodicity was 22.7 Mg ha^{-1} (Schoonover, 1952). City compost produced from Delhi (DC) and Karnal (KC) and farmyard manure (F) were neutral, slightly alkaline and basic in hydrolysis, respectively. Both the city composts contained a higher amount of soluble salts than farmyard manure (Table 1).

Table 1
Characteristics of organic amendments.

Organic amendments	Farmyard manure (F)	Karnal compost (K)	Delhi compost (D)
pH (1:5)	8.69 ± 0.03[a]	7.33 ± 0.005[b]	7.09 ± 0.01[c]
EC (1:5; dS m^{-1})	9.86 ± 0.70[b]	11.98 ± 0.67[a]	11.55 ± 0.42[a]
Total organic C (%)	10.58 ± 0.04[a]	5.52 ± 0.78[c]	6.89 ± 0.06[b]
Total N (%)	1.02 ± 0.05[a]	0.64 ± 0.09[b]	0.67 ± 0.11[b]
Ash (%)	49.88 ± 10.2[b]	83.95 ± 18.3b	80.15 ± 19.6[b]
Total Ca (g kg^{-1})	8.83 ± 0.29[b]	40.33 ± 1.15[a]	21.0 ± 1.00[b]
Total Mg (g kg^{-1})	86.2 ± 1.50[ab]	47.8 ± 5.57[c]	65.1 ± 1.08[a]
Total Na (g kg^{-1})	4.15 ± 0.08	3.87 ± 0.09	3.81 ± 0.33
Total K (g kg^{-1})	21.8 ± 0.46[a]	12.31 ± 0.44[b]	10.98 ± 0.07[c]
Total Cl (g kg^{-1})	48.52 ± 7.39	37.87 ± 4.099	42.13 ± 0.820
Total Fe (g kg^{-1})	16.2 ± 3.5	16.4 ± 2.7	14.8 ± 1.2
Total Mn (mg kg^{-1})	257.6 ± 82.3[ab]	348.3 ± 42.7[a]	82.5 ± 46.2[b]
Total Zn (mg kg^{-1})	108.9 ± 27.2[c]	609.5 ± 75.8[a]	348.3 ± 53.4[b]
Total Cu (mg kg^{-1})	9.3 ± 5.4[c]	384.3 ± 38.9[a]	58.4 ± 35.6[b]
	Heavy metal		
Total Ni (mg kg^{-1})	34.2 ± 19.8[b]	45.8 ± 13.3[a]	34.8 ± 16.5[b]
Total Cd (mg kg^{-1})	nd	nd	nd
Total Cr (mg kg^{-1})	nd	Trace	Trace
Total Pb (mg kg^{-1})	nd	nd	nd

[nd: non detectable concentration during analysis; Numbers followed by different uppercase letters (a–c) significantly different at $P \leq 0.05$ by Duncan multiple range tests for separation of mean].

2.2. Soil incubation cum column leaching and irrigation water

Processed soil was amended with respective doses of the amendments *viz.*, control without amendment, 25 % recommended doses of gypsum (GR25); 50 % recommended doses of gypsum (GR50); GR25 + 10 Mg ha^{-1} of Karnal compost (GR25 K); GR25 + 10 Mg ha^{-1} of Delhi compost (GR25D) and GR25 + 10 Mg ha^{-1} of farmyard manure (GR25 F). The soil treated with respective amendments was incubated at 60 % water holding capacity for one month at room temperature (27 – 32 °C), to settle exchange reaction in soil. Soil column leaching was performed in a set of thirty-six PVC cylinders, each 30 cm long and 10.5 cm *internal diameter* with a drainage hole, arranged in a completely randomized factorial design with three replications. Around 2.5 cm thick layer of acid-washed sand (< 0.2 mm) was placed at the bottom of the column. Geotextile fabric (acid washed) placed at the bottom of the column. The incubated air-dried soils were filled into columns up to 15 cm depth by continuous tapping against a hard surface to prevent the formation of air pockets and to achieve a uniform bulk density (Chaganti et al., 2015). The final bulk density after packing was determined to be 1.35 g cm^{-3}. A thin layer of acid-washed sand ~0.25 cm followed by a filter paper was also placed on the soil surface to improve water distribution. Three replicates were setup for each treatment. Pore volume was calculated using bulk density, particle density, and column depth. The mean one pore volume of the soil column was calculated to be 560 cm^3. Saline water, with fixed total electrolyte concentration (60 me L^{-1}) and variable SAR (5 and 15 SAR) was used for leaching to simulate the water quality of the sodic/saline-sodic area of India (Table 2). The desired quality water was prepared using the formula described by Basak et al. (2015a). The leaching experiment was conducted under saturated condition at room temperature. The soil columns were slowly wetted by placing the columns in vessels containing respective quality water by capillary rise to replace the trapped air if any, and uniform leaching. Columns were drained overnight to remove excess water held in bottom sand layer, thereafter, ten pore volumes (PV) of water were applied to maintain a constant pressure head of approximately 5 cm through regulated supply from the top of the column.

2.3. Leachate and soil analysis

Collected leachate was filtered through a Whatman 40 filter paper and frozen (−20 °C) for later analyses. Standard methods were applied for the determination of pH, EC. Ca^{2+} and Mg^{2+} were estimated by AAS (Analytika Jena, ZEEnit 700p; Germany). Na^+ and K^+ were measured with a flame photometer (Systronics, India). Chloride was measured by argentometric titration (Jackson, 1973). Carbonate and bicarbonate were determined by methyl red and phenolphthalein endpoint titration. Sulphate was determined as described by Chesnin and Yien (1951) and measured with Nephelometer (SI98713; Hanna, Romania). After completion of the leaching, the soil columns were allowed to drain. Then soil in the column was air-dried in the shade for soil chemical analysis. Soil pH_s, EC_e and cationic composition were determined in aqueous soil water saturation paste extract (USSL, 1954). ESP of soils was determined by the alcoholic ammonium chloride method (Tucker, 1985). Exchangeable K^+ was subtracted from CEC in calculating exchangeable sodium ratio (ESR) (Ranjbar and Jalali, 2015). ESR is considered as the ratio of the exchangeable Na^+ (X_{Na}) to the sum of exchangeable Ca^{2+} (X_{Ca}) and Mg^{2+} (X_{Mg}), the slope of the ESR-SAR relation represented the Gapon's selectivity coefficient (K_G) of Na^+ (Eq. (ii)) and CROSS [Cation ratio of soil structural stability; (Eq. (ii)) Rengasamy and Marchuk, 2011]:

$$\mathrm{ESR} = \frac{X_{Na}}{X_{Ca} + X_{Mg}} = \mathrm{K_G} \times \frac{[Na+]}{\sqrt{[\mathrm{Ca}^{2+} + \mathrm{Mg}^{2+}]/2}} = \mathrm{K_G} \times \mathrm{SAR_e} \quad \text{(i)}$$

$$\mathrm{K_G} = \frac{\mathrm{ESR}}{\mathrm{SAR_e}} \quad \text{(ii)}$$

$$\mathrm{CROSS} = \frac{Na^+ + 0.56K^+}{((Ca^{2+} + 0.\ 6Mg^{2+})/2)^{\ 0.5}} \quad \text{(iii)}$$

Soil organic C was determined by the wet oxidation method (Walkley and Black, 1934). Calcium carbonate equivalent was measured by neutralization with HCl (Allison and Moodie, 1965). Total C and N content of city waste compost and farmyard manure were determined in CHNS analyzer (Elementar Vario EL III, Germany). The cation and anion concentration and heavy metals in di-acid digest of compost and farmyard manure were estimated using AAS.

2.4. Ionic balance

The ionic balance (Qi) in the soil leachates was calculated for each treatment. The cumulative amount of ions in the leachate relative to the amount in the incoming water was calculated as described by Jalali and Ranjbar (2009):

$$Qi = \sum (Cij - Cis) \times Vj$$

Where, C_{ij} and C_{is} are the ion concentrations in the leachate and the incoming solution, respectively, at a collected volume, Vj. A positive Q_i shows the addition of ion to the leachate from the soil when compared with the incoming solution, whereas a negative value points out the removal of ions from the incoming solution.

Following equation was applied to calculate pH/EC/SAR index of leachates collected after the ten consecutive pore volumes applied:

$$pH_{Le} = \frac{[pH_{mean} - \sigma]}{pH_{max}}\ ;\ EC_{Le} = \frac{[EC_{mean} - \sigma]}{EC_{max}};\ and\ SAR_{Le} = \frac{[SAR_{mean} - \sigma]}{SAR_{max}}$$

Where, $pH_{mean}/EC_{mean}/SAR_{mean}$ = mean pH/EC/SAR over the PV-I to X, σ = standard deviation of pH/EC/SAR in pore volume, pH/EC/SAR_{max} = maximum pH/EC/SAR among the pore volume.

2.5. Statistical analysis

Statistical analysis of the data was performed using SAS 9.3. Normality and heterogeneity of database checked using Shapiro Wilk's and Bartlett's Test. The analysis of variance (ANOVA) was developed to determine the statistical significance of treatment effects. The 'Tukeys Test' was used to compare treatment means. Further, separate principal component analysis (PCA) was performed for SAR 5 and SAR 15 using twenty six attributes representing cationic composition of exchange phase (Ca_x, Mg_x, Na_x and K_x) and attributes of soil exchange phase (CEC and ESP), $CaCO_3$, soil salinity (EC_e and pHs) and sodium adsorption ration of soil solution phase (SAR_e) and Gapon's coefficient (K_G). The water quality attributes [leachates pH index (pH_{Le}), leachates EC index (EC_{Le}), leachates Ca^{2+}, Mg^{2+}, Na^+ and their balance Ca^{2+} balance ($Ca_{_B}$), Mg^{2+} balance ($Mg_{_B}$), Na^+ balance ($Na_{_B}$), leachates K^+, CO_3^{2-}, HCO_3- and SO_4^{2-}, and Cl-. Balance ($Cl_{_B}$) of leachates were accommodated in this multivariate analysis (Kaiser, 1960). Principal components (PC) receiving high eigenvalues (> 1.00) and variables with high factor loadings with such components were kept for the screening of minimum data set (MDS) (Norman and Streiner, 2008). In each PC, only highly weighted factors, *i.e.* those with absolute values within 10 % of the highest weight, were screened for the MDS. Simple correlation coefficients were also computed to evaluate the relationships among the response variables.

Table 2
Ionic composition of synthetic saline-SAR water.

SAR ($mmol^{1/2}\ L^{-1/2}$)	Total electrolyte concentration (100.0 me L^{-1})		
	Na^+	Ca^{2+}	Mg^{2+}
5	29.65	46.99	23.49
15	63.81	24.13	12.06

Table 3
Gypsum and conjunctive use of gypsum and organic amendments affect soil pH_s and EC_e (dS m^{-1}) after incubation.

Treatments	pH_s	EC_e
Control	10.34^{a}	15.84^{a}
GR25	10.21^{ab}	18.42^{a}
GR50	9.96^{d}	19.40^{a}
GR25F	10.01^{cd}	17.93^{a}
GR25K	10.16^{bc}	19.60^{a}
GR25D	10.22^{ab}	18.75^{a}
Contrast	pH_s	EC_e
Control *vs.* GR25K/D	**	**
GR25 *vs.* GR25K/D	ns	ns
GR50 *vs.* GR25K/D	***	ns
Control *vs.* GR25F	***	**
GR25 *vs.* GR25K	**	ns
GR25 *vs.* GR25D	*	ns
GR25F *vs.* GR25 K/D	**	ns

[Numbers followed by different uppercase letters (a–d) significantly different at $P \leq 0.05$ by Duncan multiple range tests for separation of mean].

3. Results

3.1. Changes in soil pH_s and EC_e after incubation

Amending soil with gypsum (50GR) and 25GRF decreased soil pH up to 0.2 and 0.15 units, respectively, and increased by 0.18 unit in unamended soil compared to initial soil ($P > 0.05$) (Table. 3). Whereas, the change in pH_s after addition of GR25 and GR25 + K/D was significant compared to initial values. During incubation, the EC_e increased by 30, 50, 59, 47, 61, and 46 % in C, GR25, GR50, GR25 F, GRK and GRD, respectively (Table 3).

3.2. Cumulative leaching of cations and anions

Amendments and water quality affected the leaching of electrolytes. The increment in SAR of applied water declined cumulative loss of cations (Ca^{2+}, Mg^{2+} and K^{+}) and released more Na^{+} (Table 4). Ca^{2+} and Mg^{2+} loss were declined 3.5 and 2.2 times less for SAR 15 compared to SAR 5 because of less supply of Ca^{2+} and Mg^{2+} during leaching. Further control noted a limited loss of Ca^{2+}/Mg^{2+}. Oppositely, gypsum applied in reduced dose (GR25) recorded increased Ca^{2+}/Mg^{2+} release in leachate. The exchange phase in these soils showed greater affinity for Ca^{2+}/Mg^{2+} available in the soil solution. In GR25 + F/K/C treatments, mineralization of manure and dissociation of gypsum liberated an excess amount of fixed Ca^{2+}/Mg^{2+}. Soil amended with GR25 + F/K/C, and GR50 lost a larger quantity of K^{+} than control when SAR 5 was used for leaching. Release of ${CO_3}^{2-}$ was higher in control followed by GR25 > GR25 + F/K/D > GR50.

Table 5
Gypsum and conjunctive use of gypsum and organic amendments affect leachates quality index.

Treatment	pH_{Lin}	EC_{Lin}	SAR_{Lin}
Control	0.80^{ab}	0.31^{ab}	0.27^{ab}
GR25	0.80^{ab}	0.32^{a}	0.31^{a}
50GR	0.81^{a}	0.30^{b}	0.24^{bc}
GR25F	0.79^{b}	0.30^{ab}	0.30^{ab}
GR25K	0.79^{b}	0.31^{ab}	0.30^{ab}
GR25D	0.80^{ab}	0.31^{ab}	0.20^{c}
SAR 5	0.78^{B}	0.30^{B}	0.11^{B}
SAR 15	82^{A}	0.32^{A}	0.43^{A}
Amendments × water quality	*	***	**
Contrast			
Control *vs.* City compost	ns	ns	ns
GR50 *vs.* City compost	*	ns	ns
GR25 *vs.* City compost	ns	*	*
GR25 K *vs.* GR25D	ns	ns	**
Farmyard manure *vs.* City compost	ns	ns	ns

[Where, $pH_{Lin}/EC_{Lin}/SAR_{Lin}$ = pH/EC/SAR index of leachates; Numbers followed by different uppercase letters (a–c) significantly different at $P \leq 0.05$ by Duncan multiple range tests for separation of mean].

3.3. pH, EC, and SAR of soil leachate

The breakthrough curves (BTCs) of the leachate pH showed alkaline to high pH when leached with SAR 15 water, but the range was near neutral to high pH when SAR 5 water applied. Detail description of pH, EC, and SAR of BTCs in leachates has been presented in Sundha et al. (2018). This corroborates with greater leachates index of pH_{Lin} (0.82), EC_{Lin} (0.32) and SAR_{Lin} (0.43) when leaching performed was by SAR 15 than SAR 5 (0.78, 0.30 and 0.11 of pH_{Lin}, $EC_{Lin,}$ and SAR_{Lin}) (Table 5).

3.4. Changes in pH and EC after leaching

Application of amendment and intense leaching declined both pH_s and EC_e (Table 6). Observed decrement of pH_s and EC_e were greater for leaching with SAR 5 than SAR 15. Irrespective of amendments used, the soil pH_s improved to near neutral (7.77) and EC_e declined to 4.58 dS m^{-1} when SAR 5 water was applied for leaching. The pH_s resided to slight alkaline (8.02) and EC_e remained 5.20 dS m^{-1} when SAR 15 was applied for leaching.

Table 4
Amounts of cations and anions gained by or leached from different treatments under leaching with SAR water.

Treatment	Ca^{2+}	Mg^{2+}	Na^{+}	Cl^{-}	K^{+}	${CO_3}^{2-}$	${HCO_3}^{-}$	${SO_4}^{2-}$	Ca^{2+}	Mg^{2+}	Na^{+}	Cl^{-}
Water quality	Cumulative ions released during column leaching (me kg^{-1} soil)								Gain (-ve values) or loss (+ve values) of ionsin soil (me kg^{-1} soil)			
		SAR 5										
Control	15.8^{b}	8.2^{b}	306.9^{ab}	249.8^{b}	0.17^{b}	7.67^{a}	25.0^{a}	25.3^{b}	-142.7^{b}	-71.0^{b}	206.9^{ab}	87.5^{b}
GR25	19.7^{a}	11.3^{ab}	295.1^{b}	252.4^{ab}	0.20^{b}	4.9^{b}	21.3^{b}	35.6^{a}	-138.8^{a}	-68.0^{ab}	195.0^{b}	84.9^{ab}
GR50	19.0^{a}	14.1^{a}	302.5^{ab}	246.7^{b}	0.20^{b}	2.13^{d}	17.7^{c}	40.5^{a}	-139.5^{a}	-65.2^{a}	202.4^{ab}	90.7^{b}
GR25F	18.9^{a}	7.9^{b}	295.7^{b}	259.7^{a}	0.33^{a}	3.50^{c}	25.6^{a}	36.4^{a}	-139.6^{a}	-71.4^{b}	195.7^{b}	77.6^{a}
GR25K	19.0^{a}	12.3^{ab}	313.0^{a}	253.6^{ab}	0.20^{b}	5.57^{b}	21.8^{b}	36.4^{a}	-139.5^{a}	-67.0^{ab}	213.0^{a}	83.8^{ab}
GR25D	17.1^{ab}	12.6^{ab}	303.4^{ab}	250.8^{b}	0.23^{b}	5.10^{b}	22.1^{b}	38.2^{a}	-141.4^{ab}	-66.6^{ab}	203.4^{ab}	86.5^{b}
Mean	18.25	11.1	302.8	252.2	0.22	4.81	22.2	35.4	−140.3	−68.2	202.8	85.2
Water quality	SAR 15											
Control	3.7^{d}	4.0^{d}	322.0^{ab}	255.0	0.17	12.68^{a}	21.4^{c}	22.9^{c}	-77.7^{d}	-36.7^{d}	106.8^{ab}	82.4
GR25	4.4^{cd}	5.4^{b}	318.4^{ab}	260.5	0.17	5.66^{b}	20.3^{cd}	33.1^{b}	-77.0^{cd}	35.3^{b}	103.2^{ab}	76.9
GR50	6.7^{a}	6.1^{a}	320.0^{ab}	256.9	0.17	2.04^{d}	19.7^{d}	38.5^{a}	-74.7^{a}	-34.6^{a}	104.8^{ab}	80.4
GR25F	5.3^{b}	5.5^{b}	312.9^{ab}	253.3	0.21	4.04^{bcd}	25.5^{a}	37.7^{a}	-76.1^{b}	-35.2^{b}	97.7^{ab}	84.1
GR25K	4.9^{bc}	4.8^{c}	311.4^{b}	259.0	0.19	3.05^{cd}	25.5^{a}	36.4^{ab}	-76.5^{bc}	-35.9^{c}	96.1^{b}	78.4
GR25D	6.2^{a}	4.8^{c}	326.0^{a}	256.9	0.17	4.83^{bc}	22.9^{b}	39.0^{a}	-75.3^{a}	-35.8^{c}	110.7^{a}	80.6
Mean	5.2	5.1	318.5	256.90	0.18	5.38	22.6	34.6	−76.2	−35.6	103.2	80.5

[Numbers followed by different uppercase letters (a–d) significantly different at $P \leq 0.05$ by Duncan multiple range tests for separation of mean].

Table 6
Gypsum and conjunctive use of gypsum and organic amendments affect soil pH_s and EC_e (dS m^{-1}) after incubation.

Treatments	pH_s	EC_e	ΔpH_s	ΔEC_e
Control	8.01	4.67^{b}	2.15^{b}	7.48^{a}
GR25	7.94	4.71^{b}	2.22^{ab}	7.44^{a}
GR50	7.9	5.07^{ab}	2.26^{ab}	7.08^{b}
GR25F	7.79	5.17^{a}	2.36^{a}	6.98^{b}
GR25K	7.85	4.74^{ab}	2.31^{ab}	7.41^{a}
GR25D	7.9	4.97^{ab}	2.26^{ab}	7.18^{ab}
SAR 5	7.77^{B}	4.58^{B}	2.39^{A}	7.57^{A}
SAR 15	8.02^{A}	5.20^{A}	2.14^{B}	6.96^{B}
Amendments Water quality	ns	*	ns	*
Contrast	pH_s	EC_e	ΔpH_s	ΔEC_e
Control *vs.* GR25 K/D	*	ns	ns	ns
GR50 *vs.* GR25 K/D	ns	ns	ns	ns
GR25 *vs.* GR25 K/D	ns	ns	ns	ns
GR25K*vs.* GR25D	ns	ns	ns	ns
GR25F*vs.* GR25 K/D	ns	*	ns	*

[Numbers followed by different uppercase letters (a–e) significantly different at $P \leq 0.05$ by Duncan multiple range tests for separation of mean].

3.5. Composition of aqueous soil water saturation paste extract after leaching

Like soil pH_s and EC_e, water quality has an overriding influence on aqueous soil water saturation paste extract (Table 7). Leached soil contained a higher amount of Ca^{2+}, Mg^{2+}, K^+, Cl^- and HCO_3^- and a lower amount of Na^+ and SO_4^{2-} when SAR 5 was applied for leaching than SAR 15.

3.6. Changes in CEC, ESP and $CaCO_3$

The observed CEC values in these amended soils were lower than the initial value, but it was 16, 34, 30, 33 and 30 % greater in GR25, GR50, GR25F, GR25K and GR25D, respectively, compared with control. Amended soil with GR50 and GR25 + F/D/K showed higher values of soil CEC compared to control. The lowering of CEC was more in SAR 15 compared with SAR 5 water. Except for control, amendments declined in ESP (ESP < 15) after leaching with ten pore volumes of SAR 5. ESP reductions were significantly higher ($P < 0.01$) in amended soils than in control (Table 8). ESP of both control and amended soils remained > 15 % when leached with SAR 15. Further, the ESP of control soil was higher with SAR 15 (Fig. 1). Soil $CaCO_3$ declined from the initial value, and the maximum decline was observed in control followed by GR25 and GR25F. SAR 5 had lower $CaCO_3$ content compared with SAR 15 (Table 8).

Table 7
Gypsum and conjunctive use of gypsum and organic amendments affect ionic composition of aqueous soil water saturation extract (me L^{-1}) after incubation.

Treatment	Ca^{2+}	Mg^{2+}	Na^+	K^+	Cl^-	SO_4^{2-}	HCO_3^-
Control	7.27	7.00^{b}	35.73	1.14^{c}	41.78	0.23^{a}	2.59
GR25	7.34	7.10^{b}	36.11	1.12^{c}	41.09	0.20^{ab}	2.33
GR50	8.12	6.28^{b}	34.86	1.29^{bc}	40.89	0.22^{ab}	2.38
GR25F	8.47	9.43^{a}	34.93	1.75^{a}	40.71	0.22^{ab}	2.53
GR25K	7.96	8.47^{ab}	34.59	1.55^{ab}	41.78	0.25^{a}	2.73
GR25D	7.02	8.28^{ab}	34.44	1.38^{bc}	41.31	0.17^{b}	2.49
SAR 5	9.15^{A}	10.82^{A}	30.40^{B}	1.53^{A}	44.89^{A}	0.20^{B}	2.83^{A}
SAR 15	6.24^{B}	4.69^{B}	39.82^{A}	1.22^{B}	37.62^{B}	0.23^{A}	2.17^{B}
Amendments * Water quality	ns	**	*	ns	ns	ns	ns
Contrast	Ca^{2+}	Mg^{2+}	Na^+	K^+	Cl^-	SO_4^{2-}	HCO_3^-
Control *vs.* GR25K/D	ns	ns	ns	*	ns	ns	ns
GR50 *vs.* GR25K/D	ns	*	ns	ns	ns	ns	ns
GR25 *vs.* GR25K/D	ns	ns	ns	*	ns	ns	ns
GR25K *vs.* GR25D	ns	ns	ns	ns	ns	**	ns
GR25 F *vs.* GR25K/D	ns	ns	ns	*	ns	ns	ns

[Numbers followed by different uppercase letters (a–c) significantly different at $P \leq 0.05$ by Duncan multiple range tests for separation of mean].

Table 8
Gypsum and conjunctive use of gypsum and organic amendments affect cation exchange capacity (CEC), exchangeable sodium per cent (ESP), sodium adsorption ratio of aqueous soil water saturation paste extract (SAR_e), cation ratio of soil structural stability (CROSS) and $CaCO_3$ of soil after leaching.

Treatment	CEC [$cmol_{(p+)}$ kg^{-1}]	ESP (%)	SAR_e ($mmol^{1/2}$ $L^{-1/2}$)	K_G ($mmol^{1/2}$ $L^{-1/2}$)	CROSS	$CaCO_3$ (%)
Control	15.4^{c}	29.6^{a}	13.8	0.03^{a}	11.2	1.04^{d}
GR25	17.9^{b}	15.4^{b}	14.0	0.012^{b}	11.1	1.15^{c}
GR50	20.7^{a}	13.3^{b}	13.6	0.010^{b}	10.7	1.37^{a}
GR25F	20.1^{a}	15.0^{b}	13.0	0.012^{b}	10.6	1.20^{c}
GR25K	20.5^{a}	15.8^{b}	13.0	0.013^{b}	10.4	1.31^{ab}
GR25D	20.0^{a}	14.3^{b}	13.1	0.012^{b}	10.4	1.27^{b}
SAR 5	20.0^{A}	11.9^{B}	9.7^{B}	0.014^{B}	7.9^{B}	1.20^{B}
SAR 15	18.2^{B}	22.6^{A}	17.2^{A}	0.017^{A}	13.6^{A}	1.25^{A}
Amendments * Water quality	**	***	ns	**		**
Contrast	CEC	ESP	SAR	K_G	CROSS	$CaCO_3$
Control *vs.* GR25 K/D	***	***	ns	***	ns	***
GR50*vs.* GR25 K/D	ns	ns	ns	ns	ns	*
GR25*vs.* GR25 K/D	***	ns	ns	ns	ns	***
GR25K*vs.* GR25D	ns	ns	ns	ns	ns	ns
GR25 F *vs.* GR25 K/D	ns	ns	ns	ns	ns	**

[Numbers followed by different uppercase letters (a–c) significantly different at $P \leq 0.05$ by Duncan multiple range tests for separation of mean].

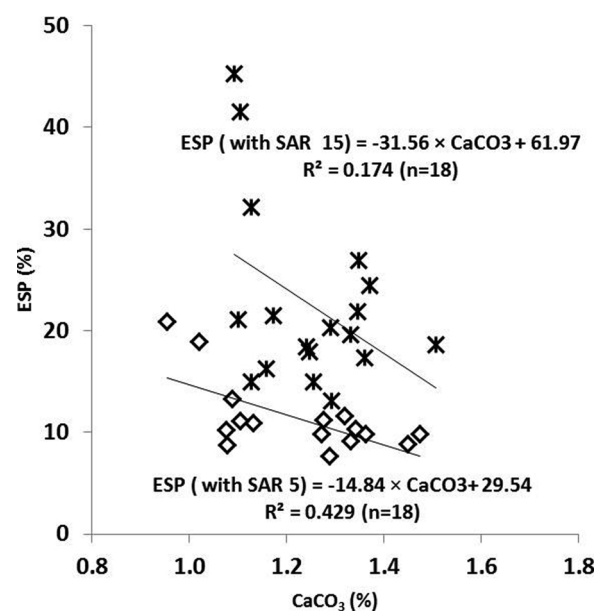

Fig. 1. ESP and $CaCO_3$ relation for soil leached with different SAR water.

3.7. SAR_e, K_G and CROSS

All the organic treatments had similar values for SAR_e, K_G and CROSS. Intensive leaching of incubated soil reduced sodium adsorption ratio (SAR_e) of aqueous soil water saturation extract from an initial level (Table 8). Na^+ removal reduced soil SAR_e in all treatments. The reduction of SAR_e was more significant when SAR 5 (9.7) water applied for leaching than SAR 15 (17.2). Gapon's selectivity coefficient (K_G) and cation ratio of soil structural stability (CROSS) was higher (0.017 and

13.6) in the soil when SAR 15 was applied for leaching than SAR 5 (0.014 and 7.9) (Table 8).

3.8. Discussion

In interpreting the behavior of sodic soils, cation exchange equilibria involving Ca-Na exchange is of considerable importance. In soils formed under N_2CO_3 type of salt, increasing sodium saturation of the system is accompanied by an increase in pH of the soil (Gupta et al., 1984). Application of gypsum in such soils alter the electrolyte concentration and composition of solution and exchange phase through the dissolution-exchange reaction. The increased soluble Ca^{2+} leads to precipitation of the calcite (Lindsay, 1979) with consequent release of protons [$Ca^{2+} + CO_2 + H_2O \leftrightarrow CaCO_3$ (Calcite) $+ 2H^+$]; which is responsible for lowering of the soil pH. Ulrich (1991) also noted that chemical hydrolysis of electrolytes and organic compounds with different functional groups play a great role in the equilibrium of soil pH. High soil organic carbon favours the preferential adsorption of Ca in exchange sites (Poonia and Tabibudeen, 1977; Gupta et al., 1984) with a consequence of reduced alkaline hydrolysis of exchangeable Na. Our results also clearly suggest that the application of different composts in conjunction with gypsum (GR25) caused a reduction in soil pH. The response of soil pH varied with compost type. Despite having high Ca content in city compost, the soil pH reduction was more in FYM. In conjunctive treatments, Ca supplied from the compost has less significance in comparison to the amount supplied through gypsum. Therefore, variable response may be because of higher organic carbon content in FYM (10.58 %) compared to both the city compost (5.52–6.89 %). Poonia and Pal (1998) also noted that applied organic matter produces clay-humus complex and divalent Ca prefer formation of complex. With increment of organic carbon, the closely spaced functional group present in organic matter raise the surface charge density (SCD) and facilitate selectivity towards multivalent cations (Poonia and Tabibudeen, 1977; Gupta et al., 1984). Choudhary et al. (2011) also reported the variable response of FYM, green manure, and wheat straw reducing soil pH of sodic soils. Besides, dissolution of gypsum and selective adsorption of Ca^{2+}, mineralization of farmyard manure, and city compost also release free organic acids which neutralize alkalinity in gypsum and manure/city compost treated soils (Chaganti et al., 2015). The little change in soil pH_s after incubation for GR25 and GR25 + K/D was attributed to the high alkalinity of sodic soil (ESP 77.5 %). The decomposition of manure increased the ionic concentration, and organic acids mobilized the dissolution of native carbonate minerals (Choudhary et al., 2011). The high electrolytes concentration in manure/composts also favored for increment of EC_e in the soil.

Retention of strong alkalinity during incubation and alkaline hydrolysis during leaching released a more significant amount of CO_3^{2-} in unamended control soil (follow Sundha et al., 2018). Leaching with SAR 15 water favoured greater CO_3^{2-} release compared to SAR 5. Strong alkali hydrolysis with application of high SAR water released more CO_3^{2-}. However, other studies reported non-detectable CO_3^{2-} concentration in leachates when sodic soils leached with water of varying SAR (Jalali and Ranjbar, 2009; Zarabi and Jalali, 2012). GR50 caused greater precipitation of calcite because of increased Ca level in soil solution with consequent reduction in CO_3^{2-} concentration in leachates. However, GR25 + F/K/D favoured the precipitation of calcite by double decomposition reaction and neutralization of CO_3^{2-} by organic acids released during organic matter decomposition may be responsible for significant reduction in the CO_3^{2-} concentration in leachates of both water qualities. An increase in the HCO_3^- content in GR25 + F/K/D compared to GR25 also indicated the increased organic acid production because of manure/compost decomposition. This supports the work of Sadegh-Zadeh et al. (2018), who observed the neutralization of some amount of CO_3^{2-} by organic acids released during decomposition of manure. Application of low SAR water regulated the release of Ca^{2+}/Mg^{2+}. However, soil amendments showed a dominant role in the release of $Ca^{2+}$and Mg^{2+} when SAR 15 water was applied for leaching. Soil amendments GR50 or GR25 + F/K/D released a larger quantity of Ca^{2+}, Mg^{2+} and K^+ than control. The external supply of Ca before incubation favored the losses of divalent cations under the influence of high SAR water. Na^+ saturation in exchange phase and abundance of Na^+ in solution phase for control soils preferred Ca^{2+} and Mg^{2+} from applied water for exchange reaction. Ranjbar and Jalali (2011) have also reported that decomposition of organic amendment results in the release of additional K^+ during leaching.

Contrary to CO_3^{2-} and HCO_3^-, the release of SO_4^{2-} was higher in amended soil than the control because of dissolution of gypsum and double decomposition reaction of Na-clay and $CaSO_4.\ 2H_2O$ and producing leachable Na_2SO_4. The soil under control gained the maximum quantity of Ca^{2+}/Mg^{2+} during leaching when SAR 5 water was applied. Amended soil had undergone for cation exchange reaction [Na_x^+–Soil-$Na_x^+ + Ca^{2+}/Mg^{2+} \leftrightarrow$ Soil-$Ca_x^{2+} + 2Na^+$; x: denote exchangeable cations] during incubation, whereas un-amended control soil still retained higher sodicity during leaching. Mixing and displacement of soil water with divalent cations rich water (SAR 5) supplied external soluble Ca^{2+}/Mg^{2+} and promoted exchange reactions during leaching. Similarly, control soil leached with SAR 5 gained an excess Ca^{2+}/Mg^{2+} compared to SAR 15 water.

Alkaline hydrolysis of inherent Na_2CO_3, $NaHCO_3$, and Na-clay produced CO_3^{2-} and HCO_3^- and showed high pH in leachates at initial pore volumes (follow Sundha et al., 2018). Prolong leaching with neutral salts and absence of CO_3^{2-} declined leachate pH in a later stage. The supply of larger amount of Na^+ on applying SAR 15 water noted the higher values of leachates pH than SAR 5. The external supply of Na promotes alkaline hydrolysis and raises the leachate pH and electrolytes concentration (Li and Keren, 2009). Application of various treatments showed comparable index values of EC_{Lin}, but leachate index (pH_{Lin} and SAR_{Lin}) reduced when organic amendment (F/K/D) was conjunctively applied with GR25. The application of SAR 5 water facilitated exchange reaction at a faster rate and improved soil physical properties, favoured to leach larger quantity of salts (Annabi et al., 2007). Water quality had overriding influence over soil amendment as soil pH_s significantly reduced after leaching with SAR 5 (Table 6). The intense leaching with SAR 5 met the Ca^{2+} demand and neutralized soil alkalinity. The application of amendments significantly declined soil pH ($P > 0.05$). Conjunctive use of gypsum with compost was equally effective as GR50 on decrement of soil pH_s and leaching of soluble salts. Further, both the city composts were equally effective for the decrement of soil pH_s and EC_e.

The non-detectable CO_3^{2-} concentration in aqueous water saturation paste of SAR 5 water leached soil indicated the neutralization of alkalinity and the progress of reclamation. Further, amendment × water quality interaction reported a significant change in Na^+ ($P > 0.05$) and Mg^{2+} ($P > 0.01$) concentration in aqueous soil water saturation paste extract. The observed changes in aqueous phase may be due to the exchange reaction and preferential loss of Mg^{2+} from exchange sites (Udo, 1978). The similar ionic concentration of Ca^{2+} and Na^+ for all the treatments was because of the overriding influence of water quality during intensive leaching. Further, the increasing concentration of Mg^{2+} and K^+ in aqueous soil water saturation paste of compost amended soils may be because of release from compost (Table 1).

The intensive leaching of soil with different SAR water resulted in declined soil CEC because of the lowering of variable charge associated with loss of dissolved organic matter and calcite under the influence of percolating water of different SAR. Application of external Ca in these soils results in a decrease of variable charge component of the CEC with a decrease in soil pH (Gupta et al., 1985). The development of negative charge at high pH may be because of either preferential hydrolysis of surface Ca^{2+} ion or because of hydrolysis of the bulk solution ions,

followed by adsorption of resulting complexes on the surfaces. Lowering of soil pH below the point of zero charges (8.0–9.5) during reclamation causes reduced negative charge of calcite. Leaching with low SAR water favoured to pick more divalent cations in exchange complex than Na^+ and K^+, facilitated greater flocculation of soil and less loss of the soil organic carbon with leachate (data not presented), therefore, greater values of CEC (Table 8). The observed CEC further supported relatively lower reduction in the variable charge after intense leaching of Ca amended soil in different treated soils. The application of manure primarily increased the saturation of Ca^{2+}, Mg^{2+}, K^+ in soil exchange sites and prevented the entry of Na^+ (Chaganti et al., 2015). Similarly, Aggelides and Londra (2000) reported an increase in soil CEC after application of city compost.

Our findings were similar to the earlier report of concomitant change in ESP with SAR of applied water (Jalali and Ranjbar, 2008; Ranjbar and Jalali, 2011; Gharaibeh et al., 2011). GR50 and GR25 + F/KC/DC were equally effective in reducing soil ESP ($P > 0.05$) as dissolution of gypsum supply Ca^{2+}, decomposition of manure and compost released Ca^{2+}, Mg^{2+} and produced organic acids which mobilized native $CaCO_3$, and likely eased Na^+-Ca^{2+}/Mg^{2+} exchange rates between soil water and exchange sites. The $CaCO_3$ dissolution reduced in gypsum-treated soil as an external supply of Ca^{2+} retarded the rate of carbonation reaction. The free Ca^{2+} perhaps maintained a Ca^{2+} balance in soil solution and satisfied the Ca^{2+} demand of saline-sodic soil for reclamation. The $CaCO_3$ dissolution was higher with farmyard manure (F) than compost probably because of faster decomposition of manure than compost.

A greater supply of Ca^{2+} and Mg^{2+} by SAR 5 helped to replace Na^+ from exchange sites and allowed its release through leaching, thus decline in soil SAR_e. Added Ca^{2+} availability from gypsum in GR25 + F/K/D helped the Na^+ displacement from exchange sites and therefore encouraged more significant decline of soil SAR_e (13.0, 13.0 and 13.1) in these treatments than control (13.8). Other researches claimed a significant decrement of SAR_e in the organic + gypsum-treated soil compared to control (Tazeh et al., 2013; Ranjbar and Jalali, 2011). The Ca^{2+}/Mg^{2+} abundance in SAR 5 compressed diffused double layer and enable the negatively charged clay surface to interact strongly with Ca^{2+}/Mg^{2+} in the vicinity (Shainberg et al., 1980). Basak et al. (2015b) and Chaudhari and Somawanshi (2002) also reported higher values of K_G for all the soils equilibrated with saline SAR (5 to 30 $mmol^{1/2}\ L^{-1/2}$) water. The K_G values were at par in the range of 0.010–0.013 ($mmol^{1/2}\ L^{-1/2}$) when amended with GR50, GR25 + F/K/D and higher value (0.03) was found in control ($P > 0.05$). These K_G values of Na^+ were quite similar to the values reported for salt-affected soil [0.014–0.021 ($mmol^{1/2}\ L^{-1/2}$)] (Aboulroos, 1975). This indicates adsorption preference of Ca^{2+} and Mg^{2+} on the exchange complex when leached with SAR 5. This adsorption affinity of soil exchange phase was shifted for Na^+ in place of Ca^{2+}/Mg^{2+} when leached with SAR 15. This is further corroborated with the observed difference in slope of ESR-SAR relation of both water quality (Fig. 2). The slope value of ESR-SAR relation were 0.061 and 0.006 $mmol^{1/2}\ L^{-1/2}$, for SAR 15 and SAR 5, respectively. The smaller values of K_G and CROSS denote that Ca^{2+}/Mg^{2+} distribution in the solid phase is more compared to the solution phase and *vice versa*. The CROSS values were at par when compared with different sodic soils in Australia. Water quality had significant impact on the CROSS value, and higher SAR irrigation water may cause more dispersive clay and unstable soil aggregation (Rengasamy and Marchuk, 2011).

Water quality had a major influence on sodicity reclamation. Therefore, separate PCA was performed for SAR 5 and SAR 15. For SAR 5, first and second principal component (PC1 = 35.5 %, PC2 = 21.3%) accounted for ~57% of the total data variation (Fig. 3a; Supplementary Table 1). In PC1, exchangeable Ca (Ca_x), SO_4^{2-} in aqueous soil water saturation extract, CEC, $CaCO_3$, and ESP in soil were identified. To reduce the redundancy, only leached Ca_x (highest positive coefficient) and ESP (highest negative coefficient) were selected in MDS as others

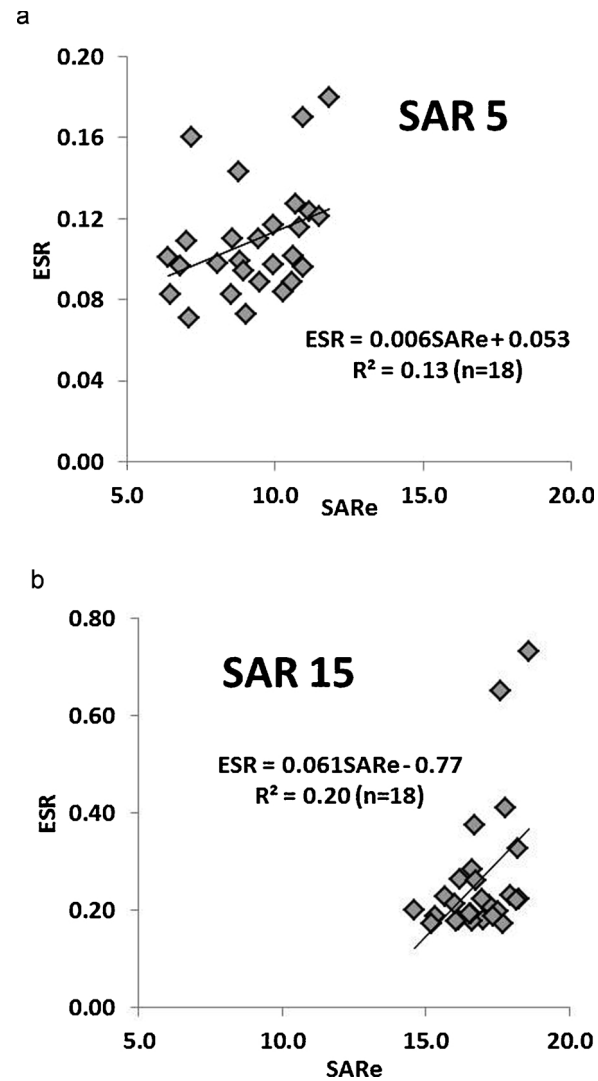

Fig. 2. ESR-SAR_e relation for soil leached with different SAR water.

were auto-correlated variables (Supplementary Table 2). Ca_x and ESP represent the presence of Ca and dominance of Na in the soil exchange phase. Reclamation with SAR 5 water depends on inherent ESP level of soil and availability of Ca^{2+} in the exchange phase (Ranjbar and Jalali, 2011). Intensive leaching with low SAR water favour displacement and mixing of the soil water with Ca^{2+}/Mg^{2+} rich water. The supply of divalent ions increases the Na^+- Ca^{2+}/Mg^{2+} exchange rates between soil water and exchange sites (Basak et al., 2015b). PCA generated for SAR 15 accounted for ~51 % of the total variation within PC1 (34.9%) and PC2 (16.5%) (Fig. 3b; Supplementary Table 3). In PC1; K_G, ESP, Na_x, and Ca_x were identified. To reduce the redundancy, only K_G (highest positive coefficient) and Ca_x (highest negative coefficient) were selected in MDS as others were autocorrelated variables (table not shown). Exchangeable Ca (Ca_x) was selected as representing the presence of Ca in the exchange phase (Supplementary Table 4). The water quality had an overriding influence in the exchange phase. Therefore, identification of K_G is rational. Selectivity coefficient becomes more prioritized with an increase of soil ESP (Singh et al., 2018a; Ranjbar and Jalali, 2015). Here, soil showed a greater value of ESP when leached with SAR 15 than SAR 5. The Cl^- balance in leachates ($Cl_{_B}$) and pH_s were screened from PC2. As chloride salts were used to simulate salinity in applied water, therefore Cl^- balance had some priority to leached soluble salt during reclamation. The pH_s define the state of soil reaction and level of alkalinity in the soil. The soil showed high pH_s when SAR 15 was used for reclamation than SAR 5 (8.02 > 7.77; $P > 0.01$).

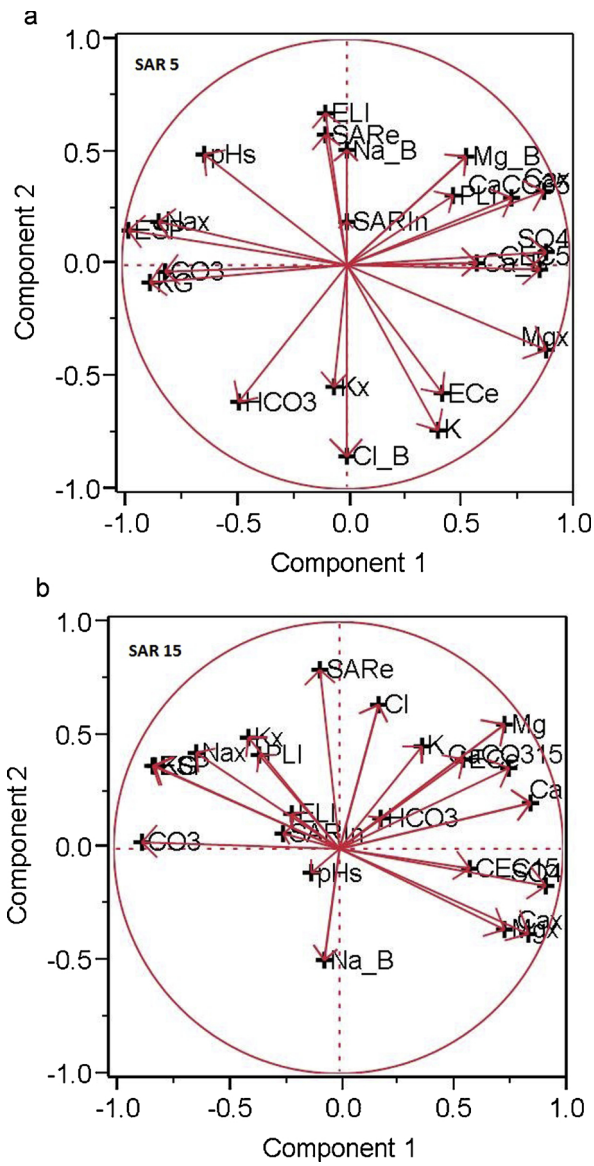

Fig. 3. Biplot for principal components (PC1 & PC2) for soil when leached with SAR 5 and 15 water.

Therefore selecting pHs is rational.

4. Conclusion

Reclamation of saline-sodic soil is vital for improving agricultural productivity. A lower dose of gypsum (25 % GR) in combination with city compost at 10 Mg ha^{-1} proved most effective in reducing soil alkalinity, leaching soluble salt, and declining soil exchangeable sodium per cent than the common recommended dose of gypsum (GR50). Quality of water used for leaching influences the reclamation of saline-sodic soil. Care should be taken while using high SAR water for irrigating saline-sodic soils as it favoured for increased CROSS index. Reclamation using SAR 5 water depends on inherent soil exchangeable sodium percent values and availability of Ca^{2+} in the exchange phase; whereas, selectivity coefficient (K_G) becomes more prioritized when SAR 15 water applied for leaching.

Declaration of Competing Interest

None.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.still.2020.104608.

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