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Full Length Article

Effect of Chemical Reclamation on the Physiological and Chemical Response of Rice Grown in Varying Salinity and Sodicity Conditions

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Abstract

Salinity and sodicity are the major abiotic constraints that prevail in arid and semi-arid regions. Proper management is required for productive use of this land. Reclamation of sodic and saline-sodic soils is highly site-specific that describes the diverse response of different soils to different amendments. These reclamation practices also alter the plant's physiological and ionic characteristics. This experiment aimed to better understand the physiological and ionic responses of rice crop at different salinity/sodicity levels. A lysimeter experiment was set forth with soil having EC_e (dS m^{-1}):SAR (mmol $L^{-1})^{1/2}$ levels as 4:20, 8:40, 12:60 and 16:80 and all the levels were treated with organic (farm manure at 25 Mg ha^{-1}) and inorganic (gypsum at 100% soil gypsum requirement (SGR) and sulphuric acid equivalent to 100% SGR) amendments keeping no ammendment as control. Results revealed that the maximum relative increase in physiological attributes (photosynthetic rate, transpiration rate, stomatal conductance and total chlorophyll contents), ionic contents (nitrogen, potassium and K:Na ratio) and growth of rice were recorded with sulphuric acid application followed by gypsum. On an average 25%, 31% and 45% increase in biological yield, plant height and paddy yield, respectively was observed with sulphuric acid application over control. It is concluded that sulphuric acid and gypsum both were the best amendments for reclamation of soil having a low level of salinity/sodicity whereas, at higher salinity/sodicity levels, only sulphuric acid seemed better for improved rice production.

Keywords: Rice; Gas exchange attributes; Salinity; Sodicity; Amendments; Reclamation

Introduction

The excess of soluble salts in agricultural land leads to soil salinity and the conditions become more severe when sodicity (a high amount of exchangeable sodium (Na^+)) prevails, which not only disturbs the nutrient dynamics but also degrade the soil structure. Soil salinity and sodicity are two of the world's most important soil issues, especially in arid and semi-arid regions. Around the globe, above 8×10^8 ha of land is salt degraded either by salinity (3.4×10^8 ha) or sodicity (5.6×10^8 ha) (Shahid *et al.* 2018). Salt degraded area of Asia (194.7×10^6 ha of saline and 121.9×10^6 ha of sodic) accounts for about 33.9% of the world's salt-affected land (Shahid *et al.* 2018). According to the estimate of Qadir *et al.* (2014), negative impacts of salt-affected irrigated land on crop production could cost the global economy about US$ 27.3 billion annually. In Pakistan, 10×10^6 ha area is currently affected due to salinity and sodicity and is growing rapidly (Shahid *et al.* 2018).

Mostly the salinity and sodicity exist together in soil which means the stress of both soluble salts and exchangeable Na^+ in a medium. Salinity combined with sodicity is more harmful to plant growth than salinity alone (Abbas *et al.* 2021). These soils have less organic matter, a disturbed soil structure, and a lower water holding capability. Disorganized aggregate formation in these degraded soils affects soil water, nutrients, and plant development (Nan *et al.* 2016; Abbas *et al.* 2021). The deleterious effects of soil salinity/ sodicity are dependent upon the type and period of salt-affected soil. Moreover, plant species and their genetic makeup also play a remarkable role (Ata-Ul-Karim *et al.* 2016; Liu *et al.* 2020; Riaz *et al.* 2020).

Soil salinity and/or sodicity induce ion toxicity and osmotic stress, and crust formation affects plant by delaying germination (Ata-Ul-Karim *et al.* 2016). Plant growth mechanisms such as photosynthesis, stomatal conductance, nutrient balance and metabolic functions are all affected by salinity and sodicity (Nam *et al.* 2018; Zahra *et al.* 2018). The high concentration of $NaHCO_3$/ Na_2CO_3 under sodic conditions results in increased pH (> 8.5) that negatively influences nutrient uptake in plants (Liu *et al.* 2020). The

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imbalance of nutrients (excess of Na^+) in plants deteriorates the normal growth process and ultimately leads to abnormal cell functioning and plant death (Quintero *et al.* 2007).

Among the monocot crops, rice (*Oryza sativa* L.) is considered salt sensitive whereas, its tolerance level varies with genotypes because of additive gene effects (Abbas *et al.* 2013; Hussain *et al.* 2018; Sardar *et al.* 2018). In the world, 7.55×10^8 t rice has been produced in the year 2018–19 from the total harvested area of 1.62×10^8 ha with a 4.64 t ha^{-1} yield. Asia is the biggest rice producer and consumer and accounts for 92% of the world's rice production. In the year 2019, 11.11×10^6 t rice was produced from 3.03×10^6 ha in Pakistan (FAO 2020). Qadir *et al.* (2014) reported 36–69% grain yield losses in rice crop due to salinity and sodicity in comparison with their counterpart normal soils in Pakistan.

Adopting appropriate diagnosis, reclamation, and land-water management approaches can help to restore and cultivate these problematic soils and play a significant role in efficient soil and water conservation. For many decades, chemical amendments have been used for the reclamation of salt-affected soils (Kheir *et al.* 2018; Singh *et al.* 2018; Zhou *et al.* 2019). The most commonly used inorganic amendments include gypsum (Rasouli *et al.* 2013; Gonçalo *et al.* 2020) and sulphuric acid (Mahmoodabadi *et al.* 2013; Kheir *et al.* 2018). Organic amendments, such as farm manure can also be used for the reclamation of salt-affected soils (Ahamed *et al.* 2019; Leogrande and Vitti 2019).

Amelioration of sodic and saline-sodic soils is highly site-specific and illustrates how different soils react to different amendments. Many scientists have noted the effectiveness of one amendment over another in the context of a single environment (Kheir *et al*. 2018; Day *et al.* 2019). Despite this, the comparison of different responses of organic and inorganic amendments towards different soil salinity/sodicity situations requires more investigation in a broad spectrum. According to our understanding, no comprehensive study was conducted to evaluate crop ionic and physiological activity changes during the reclamation of sodic and saline-sodic soils using various organic and inorganic amendments. Therefore, this experiment was executed to understand the physiological and ionic responses of rice crop at specific salinity/sodicity levels under the application of different organic and inorganic amendments. Additionally, screening of appropriate amendments for the amelioration of soils with different EC_e:SAR levels for growing rice crop was also done.

Materials and Methods

Collection of soils and amendments

Soils used in this experiment were collected from the naturally degraded and uncultivated area, Village No. 132/GB (73° 0653, 31° 1903), located near Dijkot district Faisalabad, Pakistan. Bulk of topsoil (0–20 cm) was collected from 2 different points of barren land. The collected soil samples were ground, mixed thoroughly, sieved through a 2 mm stainless steel sieve and prepared for physicochemical analysis (EC_e, pH_s, soluble cations and anions) following the procedure described by US Salinity Lab. Staff (1954). These soils have variable EC_e and SAR (normal and saline-sodic soil) but have the same textural class (sandy clay loam). The normal soil had EC_e= 4.01 dS m^{-1}, SAR= 8.17 $(mmol\ L^{-1})^{1/2}$, pH_s= 7.44, $CaCO_3$= 4.80%, organic matter= 0.43% and CEC= 9.8 $cmol_c\ kg^{-1}$. The saline-sodic soil had EC_e= 23.5, dS m^{-1}, SAR= 87.5 $(mmol\ L^{-1})^{1/2}$, pH_s= 8.1. Amendments, *i.e*., Farm manure (FM) was collected from the dairy farm of the University of Agriculture, Faisalabad. The basic characteristics of FM were: $EC_{1:10}$ = 4.75 dS m^{-1}, pH of 7.2, total carbon (dry weight basis) = 42%, a total nitrogen (dry weight basis) = 1.75%, Na^+ = 1.28%, K^+ = 2.45%. The FM was air-dried and ground to a fine powder before application. Gypsum (80% pure) was purchased from a local fertilizer supplier and commercial grade sulphuric acid (98%) was procured from a local scientific store.

Experimental setup

The experiment was carried out in lysimeters using soils with varying salinity/sodicity at wire-house of Institute of Soil and Environmental Sciences, University of Agriculture, Faisalabad, using rice as a test crop. The metrological conditions of experimental region during this crop season were ranged as temperature min 20 and max 31°C, relative humidity 51–62%, maximum rainfall 48 mm and sunshine 6–7 h.

Soils with varying salinity/ sodicity are described as EC_e (dS m^{-1}):SAR $(mmol\ L^{-1})^{1/2}$ levels. Different EC_e:SAR levels 4:20, 8:40, 12:60 and 16:80 were developed by mixing different proportions of normal and saline-sodic soil. Normal and saline-sodic soils were mixed for each level separately at different proportions keeping in view their original EC_e and SAR value (Table 1). Polyvinyl chloride lysimeters (internal diameter 26 cm and 64 cm long) were filled with 42 kg soil after developing designed EC_e:SAR levels of soil. Four lysimeters in triplicate sets of each EC_e:SAR level were maintained. Amendments including gypsum (G) at 100% soil gypsum requirement (SGR), sulphuric acid (SA) equivalent to 100% SGR and farm manure (FM) at 25 Mg ha^{-1} were applied at each level of EC_e:SAR and one control (without addition of any amendment) were kept along. There were 16 treatments and 48 experimental units in total.

Seeds of rice cultivar 'Super Basmati' were sown in normal soil and after 35 days, seedlings were transplanted in soil-filled lysimeters maintaining four plants per lysimeter. The recommended dose of N:P:K (55:45:32.5 mg kg^{-1}) nutrients (using urea, diammonium phosphate and sulphate of potash) was applied. The full dose of P, K and 1/3rd of the recommended dose of N was applied at the time of transplanting and the remaining N was applied in two equal splits at tillering and reproductive stages. Throughout the growth period of crop, canal water having EC 0.25 dS m^{-1}, total soluble salts 2.5 mg L^{-1}, SAR 1.38 (mmol $L^{-1})^{1/2}$ and RSC Nil, was used for irrigation as per crop requirement. After 40 days of transplanting rice seedlings, gas exchange attributes, *i.e*., photosynthetic rate, transpiration rate and stomatal conductance were recorded using a portable narrow chambered infrared gas analyzer (IRGA, LCA-4, Analytical Development Company, Hoddesdon, England). Leaf total chlorophyll content index of fully expanded leaves of 40 days old plants were determined *via* SPAD-502 meter (Minolta, Osaka, Japan). Average SPAD readings were recorded from three measurements following Saqib *et al.* (2012). At maturity, the crop was harvested and different plant growth parameters (plant height, biological yield and paddy yield) were recorded. Plant samples were safely set aside for ionic analysis. After harvest, soil samples were collected from lysimeters for analysis.

Plant digestion and nutrient analysis

Harvested plant samples were washed and set in paper bags separately. These bags were placed in a drying oven at 70°C and dried till the constant weight was achieved. After grinding these plant samples (straw and paddy) in Wiley mill fitted with stainless steel blades, were digested. Di-acid mixture (HNO_3:$HClO_4$ 2:1 *v/v*) was used for this purpose. After digestion, the filtrate was stored in air-tight bottles. Total N in straw and paddy was determined by micro-Kjeldahl method (Isaac and Johnson 1976). Total P of plant samples was measured on a UV-visible spectrophotometer (Thermo Electron, Waltham, U.S.A.) after standardizing the instrument with KH_2PO_4 solutions of known concentration. Total Na and K were analyzed by Jenway PFP-7 flame photometer using standard curve drawn by running the solutions of known concentration (prepared using reagent grade NaCl and KCl) on the instrument.

Soil analysis

The post-rice harvest soil samples were collected from lysimeters by using stainless steel sampling tube. Collected samples were air-dried, ground to pass through a 2 mm sieve and stored in plastic bags. These samples were analysed for $pH_{s,}$ EC_e and soluble cations following the methods described by the US Salinity Lab. Staff (1954).

Statistical analysis

Experiment was laid out in a factorial completely randomized design (Factor 1: EC_e:SAR levels and Factor 2: Amendments) with three replications. The data were presented as mean values and the standard errors were calculated using Microsoft Excel software. The statistical analyses of data were done using Statistix v. 8.1 computer software. Analysis of variance (two-way ANOVA) and subsequent pairwise comparison was done with Tukey's HSD test at 5% probability. Radar diagrams were drawn using Origin software (v. 2019, U.S.A.) by putting relative values of plant physiological data.

Results

Physiological changes in response to applied amendments at various EC_e:SAR levels

Rice physiological parameters such as photosynthetic rate (*A*), transpiration rate (*E*), stomatal conductance (*gs*) and total chlorophyll content (SPAD) were significantly influenced by the EC_e:SAR levels and the type of amendment used, as well as their interaction. The maximum relative increase in SPAD, *A*, *E* and *gs* was observed with SA at all ECe:SAR levels except ECe:SAR level 12:60 (Fig. 1). All the recorded physiological data indicated that the increase in EC_e:SAR levels results in gradual or sharp decrease in SPAD, *A*, *E* and *gs* values. The gradual decrease was observed in SPAD and *A* whereas *E* and g_s depicted a sharp decrease at EC_e:SAR level 8:40 and then decrease gradually with increasing EC_e:SAR levels (Fig. 1e).

Growth variations in response to applied amendments at various EC_e:SAR levels

As shown in Fig. 2, the biological yield, plant height and paddy yield were significantly affected with increasing EC_e:SAR levels and type of applied amendment and their interaction. Sulphuric acid depicted maximum values for biological yield, plant height and paddy yield whereas the amendments follow the following sequence in increasing rice growth; SA > G > FM > C. The maximum increase in biological yield (37.68% relative to control) was observed at EC_e:SAR level 4:20 with SA. Considering plant height, SA remained best amendment at all EC_e:SAR levels with the maximum relative increase of 43.76% at EC_e:SAR level 4:20 followed by 40.96% at EC_e:SAR level 16:80 with respect to control. The paddy yield varies between 0.97 to 3.86 g $plant^{-1}$ with maximum value at EC_e:SAR level 4:20 and minimum value at level 16:80.

Ionic variations in response to applied amendments at various EC_e:SAR levels

Nitrogen: Nitrogen (N) concentration in straw and paddy was significantly influenced with EC_e:SAR levels, type of amendment and their interaction. In straw, N concentration varied between 0.40 and 0.65%, with maximum concentration at EC_e:SAR level 12:60 and minimum at EC_e:SAR level 4:20 (Table 2). A promising increase in N was observed with SA (24 to 36% with respect to respective controls) at all EC_e:SAR levels. In case of paddy, the maximum value (1.11%) was recorded with G at EC_e:SAR level 12:60 and the minimum (0.72%) was observed with control at EC_e:SAR level 16:80 (Table 2).

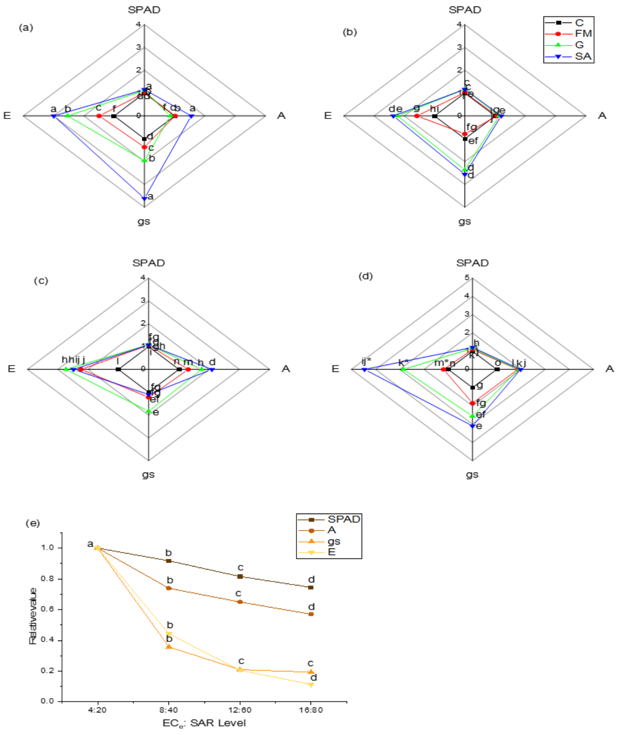

Fig. 1: Radar charts representing variation in physiological parameters of rice due to EC_e: SAR level **a**) 4:20, **b**) 8:40, **c**) 12:60 and **d**) 16:80. The status of physiological parameters with FM (red), G (green) and SA (blue) is shown relative to the control (C= black). **e**) Line chart representing the relative effect of EC_e: SAR levels on physiological parameters. * =value is presenting as divisor of 4. C= Control; FM= Farm manure at 25 Mg ha^{-1}; G= Gypsum at 100% SGR; SA= Sulphuric acid equivalent to 100% SGR. SPAD= Total chlorophyll contents, A=Photosynthetic rate, gs= Stomatal conductance and E= Transpiration rate

Common alphabets above points at an antenna represents non-significant difference at $P \leq 0.05$

Phosphorus: The straw phosphorus (P) concentration shows a variable trend with respect to both EC_e:SAR level and amendments (Table 2). However, the studied factors and their interaction have a significant effect. The P concentration in rice straw was ranged from 0.10 to 0.03%. The maximum relative increase in straw P concentration was observed with FM at EC_e:SAR level 8:40 and 12:60. Paddy P concentration was significantly varied with different EC_e:SAR levels and amendments. The maximum P concentration in paddy was observed with SA at EC_e:SAR level 4:20 whereas, G showed better results at levels 8:40 and 12:60. At EC_e:SAR level 16:80, FM performed best regarding paddy P concentration.

K:Na ratio: There was a significant variation in straw and paddy potassium:sodium ratio (K:Na ratio) due to EC_e:SAR levels, applied amendments and their interaction (Table 2). In straw, K:Na ratio varied between 0.42 and 3.58 whereas in paddy, values for K:Na ratio lies between 0.72 and 6.23.

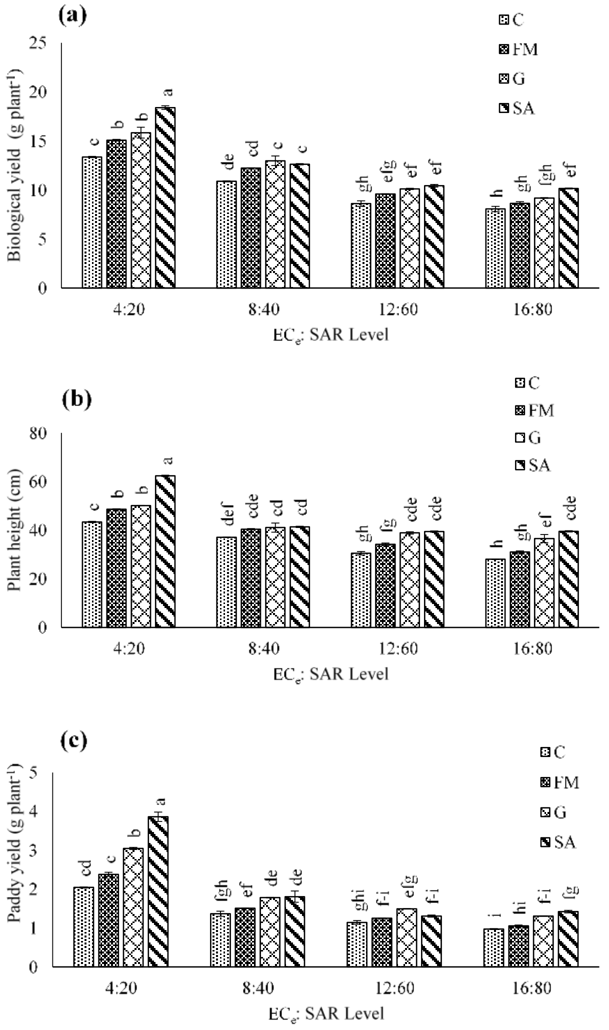

Fig. 2: Effect of EC_e: SAR levels and amendments on growth parameters of rice (**a**) biological yield (g plant^{-1}), (**b**) plant height (cm) and (**c**) paddy yield (g plant^{-1}).

C= Control; FM= Farm manure at 25 Mg ha^{-1}; G= Gypsum at 100% SGR; SA= Sulphuric acid equivalent to 100% SGR. Bars denote standard error (n=3). Common alphabets above bars represent non-significant difference at $P \leq 0.05$

The highest values for straw and paddy K:Na ratio was observed with SA treatment whereas these values decreased as EC_e:SAR level increased.

Variation in post-harvest soil chemical properties due to applied amendments at various EC_e:SAR levels

Soil EC_e: The results showed that amendments and EC_e:SAR levels had significant ($P \leq 0.05$) effects on post-harvest soil EC_e (Table 3). Overall, organic and inorganic amendments application decreased soil EC_e at all EC_e:SAR levels whereas, the decrease was more pronounced with SA and the order of amendments in reclaiming EC_e was SA > G > FM > C. The maximum relative decrease in post-harvest soil EC_e (61.09% with respect to control) was observed with

Table 1: Characteristics of soils used for rice cultivation after developing required EC_e: SAR levels prior to the experiment

Desired EC_e:SAR	Achieved EC_e:SAR	pH_s
4:20	04.5: 20.42	7.82
8:40	07.9: 38.28	8.51
12:60	12.4: 60.38	8.7
16:80	16.0: 80.23	8.81

EC_e (dS m^{-1}) and SAR (mmol $L^{-1})^{1/2}$

Table 2: Effect of EC_e: SAR levels and amendments on rice straw and paddy ions content

EC_e: SAR level		N (%)		P (%)		K (%)		Na (%)		K:Na ratio	
	Amendment	Straw	Paddy	Straw	Paddy	Straw	Paddy	Straw	Paddy	Straw	Paddy
4:20	C	0.40 g	0.81 h	0.05 fg	0.21 b-e	0.76 ab	0.25 abc	0.327 i	0.050 de	2.34 c	5.11 bc
	FM	0.45 e	0.85 gh	0.06 e	0.24 ab	0.81 a	0.27 ab	0.290 ij	0.059 cde	2.80 b	4.49 cd
	G	0.50 d	0.92 ef	0.08 c	0.24ab	0.85 a	0.28 a	0.307 i	0.049 de	2.77 b	5.68 ab
	SA	0.52 cd	0.96 de	0.10 b	0.26 a	0.86 a	0.29 a	0.240 j	0.048 e	3.58 a	6.23 a
8:40	C	0.45 e	0.83 gh	0.06 e	0.19 def	0.51 ef	0.20 de	0.477 g	0.079 c	1.07 ef	2.51 g
	FM	0.50 d	0.88 fg	0.10 a	0.22 bcd	0.62 cd	0.22 cde	0.443 gh	0.070 cde	1.40 de	3.12 efg
	G	0.54 c	1.00 d	0.08 c	0.23 abc	0.64 cd	0.23 bcd	0.403 h	0.061 cde	1.61 d	3.69 de
	SA	0.61 b	1.07 ab	0.07 d	0.20 cde	0.68 bc	0.23 bcd	0.413 h	0.066 cde	1.65 d	3.54 ef
12:60	C	0.51 d	0.93 ef	0.05 gh	0.19 c-f	0.42 fg	0.18 ef	0.667 bc	0.117 b	0.64 ghi	1.57 h
	FM	0.61 b	1.01 cd	0.10 b	0.14 g	0.55 de	0.20 de	0.623 cde	0.080 c	0.88 fgh	2.50 g
	G	0.62 ab	1.11 a	0.06 de	0.20 c-f	0.55 de	0.21 cde	0.583 ef	0.071 cd	0.95 fg	2.99 efg
	SA	0.65 a	1.09 ab	0.05 f	0.16 fg	0.58 cde	0.22 cde	0.553 f	0.074 c	1.05 ef	3.05 efg
16:80	C	0.41 fg	0.72 i	0.03 j	0.20 cde	0.33 g	0.15 f	0.780 a	0.210 a	0.42 i	0.72 i
	FM	0.43 ef	0.85 gh	0.04 i	0.22 bcd	0.41 fg	0.18 ef	0.713 b	0.120 b	0.57 hi	1.53 hi
	G	0.50 d	0.99 d	0.04 i	0.17 efg	0.48 ef	0.20 de	0.643 cd	0.079 c	0.75 f-i	2.46 g
	SA	0.51 cd	1.06 bc	0.04 hi	0.14 g	0.51 ef	0.20 de	0.590 def	0.076 c	0.87 fgh	2.71 fg

Common alphabets in a column followed by values represents non-significant difference at $P \leq 0.05$. C= Control; FM= Farm manure at 25 Mg ha^{-1}; G= Gypsum at 100% SGR; SA= Sulphuric acid equivalent to 100% SGR; N= Nitrogen; P=Phosphorus; K= Potassium; Na= Sodium.

Table 3: Effect of EC_e: SAR levels and amendments on chemical characteristics of soil

EC_e: SAR level	Amendments	EC_e	RP	SAR	RP	pH_s
4:20	C	3.20 gh	-28.89	17.17 h	-15.85	7.58 cd
(4.5: 20.4)*	FM	2.44 hi	-45.85	13.83 i	-32.21	7.62 c
	G	1.34 ij	-70.23	12.98 i	-36.36	7.55 cde
	SA	1.25 j	-72.33	12.06 i	-40.90	7.29 fg
8:40	C	6.88 e	-12.95	35.34 e	-7.68	8.30 b
(07.9: 38.28)*	FM	4.16 fg	-47.31	26.76 f	-30.09	7.37 efg
	G	4.37 f	-44.74	20.43 g	-46.64	7.38 d-g
	SA	3.88 fg	-50.89	20.92 g	-45.34	7.33 fg
12:60	C	10.69 b	-13.76	52.32 b	-13.35	8.67 a
(12.4: 60.38)*	FM	7.81 de	-36.99	40.21 cd	-33.41	8.29 b
	G	7.30 de	-41.10	28.56 f	-52.69	7.63 c
	SA	6.77 e	-45.40	26.47 f	-56.17	7.45 c-f
16:80	C	12.78 a	-20.13	70.24 a	-12.45	8.62 a
(16.0: 80.23)*	FM	9.03 c	-43.58	50.77 b	-36.72	8.36 b
	G	8.29 cd	-48.19	42.01 c	-47.63	7.36 efg
	SA	7.06 e	-55.90	38.28 d	-52.29	7.20 g

*achieved values; Unit of EC_e and SAR are dS m^{-1} and (mmol $L^{-1})^{1/2}$, respectively. Common alphabets in a column followed by values represents non-significant difference at $P \leq 0.05$. RP= relative percentage. (-) sign indicates relative decrease. C= Control; FM= Farm manure at 25 Mg ha^{-1}; G= Gypsum at 100% SGR; SA= Sulphuric acid equivalent to 100% SGR

SA at EC_e:SAR level 4:20 whereas, at EC_e:SAR level 16:80, 44.78% decrease was observed with SA as compared to control.

Soil SAR: A significant ($P \leq 0.05$) effect of amendments and EC_e:SAR levels on decreasing soil SAR were noticed. The non-significant difference in G and SA was observed in decreasing post-harvest soil SAR at EC_e:SAR level 4:20, 8:40 and 12:60 whereas, at level 16:80, a significantly higher reduction was observed with SA. Overall, the order of amendment in decreasing SAR was SA > G > FM > C (Table 3).

Soil pH_s: The significant ($P \leq 0.05$) changes in soil pH_s were observed with the studied factors. Results revealed that the application of amendments decreases the soil pH_s. The minimum pH_s 7.29, 7.33, 7.45 and 7.20 was recorded with SA at level 4:20, 8:40, 12:60 and 16:80, respectively while pH_s of control was 7.58, 8.30, 8.67 and 8.62 at level 4:20, 8:40, 12:60 and 16:80 respectively (Table 3).

Discussion

The present experiment revealed the beneficial effect of applied amendments, *i.e*., SA, G and FM in decreasing EC_e, SAR and pH_s, of post-rice harvest soil (Table 3). Application of amendments directly or indirectly increased Ca^{2+} and Mg^{2+} in soil solution that possibly replace the Na^+ present on exchange sites of soil colloids and reduces the SAR of soil. This replaced Na^+ came into the soil solution and was effectively removed from the rooting zone along with other soluble salts with the application of good quality water, which ultimately reduced the EC_e of soil (Gharaibeh *et al.* 2010; Gonçalo *et al.* 2020). The role of SA was noticeable in decreasing EC_e, SAR and pH_s of soil (Table 3). Previously considerable decrease in EC_e, SAR and pH_s of soil with SA have been reported by Mahmoodabadi *et al.* (2013) and Ahmad *et al.* (2013). The promising effect of SA in reducing SAR individually or in combination with other organic and inorganic amendments was also observed by Mahmoodabadi *et al.* (2013) and indicates the supremacy of SA over G in ameliorating sodicity. This might be due to the faster dissolution of lime with acid than the gypsum dissolution (Amezketa *et al.* 2005).

In the current experiment, improvement in physiological attributes (SPAD, *A*, g_s and *E*) with SA were promising compared with other applied amendments but in some treatments, G also performed good (Fig. 1). Cha-Um *et al.* (2011) reported a significant positive effect of G and FM on SPAD, *A*, g_s and *E* of rice plant grown in salt-affected soil. The reaction of SA with soil lime, increase both soluble Ca^{2+} and SO_4^{2-} (Mace *et al.* 1999) that play the key role in nullifying salt stress and improving physiological and growth characteristics in various plants (Helmy *et al.* 2013; Akladious and Mohamed 2018; Hussain *et al.* 2019; Riffat *et al.* 2020). The alleviation in rice SPAD, *A*, g_s and *E* also attributed to improved nutrients uptake, which plays a considerable role in the photosynthetic process, stomatal movement, osmoregulation and enzyme activation (Hasanuzzaman *et al.* 2018).

Application of amendments significantly increased N, P and K contents at all EC_e:SAR levels in rice straw and paddy (Table 2). Previous research has also shown that organic and inorganic amendments increase nutrient content (Helmy *et al.* 2013; Singh *et al.* 2018; Sardar *et al.* 2021). Overall, the highest straw and paddy N and K contents were observed with SA. However, the response of P was variable. Shaban *et al.* (2013) found the highest N, P and K content with SA compared to G and elemental sulphur in sandy loam soil having EC_e 14.8 dS m^{-1} and SAR 22.9. Such improvements may be due to the lowering of pH, EC_e and SAR of the treated soil through amendment addition and improving utilization of essential plant nutrients (Mazhar *et al.* 2011; Shaban *et al.* 2013). The synergistic effect of SA on N, P and K availability and uptake was also reported by Helmy *et al.* (2013). In contrast, it was observed that rice Na^+ contents significantly decreased with the application of SA. As applied amendments play a significant role in saline-sodic soil reclamation and removal of excessive Na^+ from root zone and thus reduce the entry of Na^+ in plants and consequently increase K:Na ratio of a plant (Jedrum *et al.* 2014).

Plant height, biological yield and paddy yield (Fig. 2) varied significantly at different EC_e:SAR levels as well as with different amendments. Similar to our results, many researchers have demonstrated that rice yield decreases with an increase in salt stress (Hussain *et al.* 2012, 2013; Hakim *et al.* 2014; Huang *et al.* 2017). At higher EC_e:SAR levels, diminished rice growth attributed to increased salinity and sodicity level than rice threshold limit, that causes osmotic effect and disturb plant ionic status. The reported threshold salinity level for rice ranged 1.9–3.0 dS m^{-1} (Grieve *et al.* 2012) and may decrease the yield greater than 50% at an EC_e of 6.65 dS m^{-1} (Cha-Um *et al.* 2011) whereas it could grow unaffectedly up to exchangeable sodium percentage level 40 (Abrol and Bhumbla 1979). Hakim *et al.* (2014) explained the reduction of grain yield under salt stress as excess salts alter the metabolic activities of the cell wall, limiting its elasticity. As a result, the cell wall becomes rigid and reduced the turgor pressure efficiency in cell enlargement.

Rice plant height, paddy yield and biological yield significantly increased with the application of SA, G and FM, whereas, the growth with SA amendment was considerably high (Fig. 2). The superiority of SA might because of its effect on decreasing soil pH, improving soil aggregation and enhancing the availability of certain plant nutrients (Niazi *et al.* 2001; Kheir *et al.* 2018). Helmy *et al.* (2013) credited the improvement in growth parameters to direct and indirect source of Ca^{2+}, that is required for a variety of plant functions, among which appropriate cell division and elongation, enzyme activity and metabolism are primary. Similar results were also reported by Mazhar *et al.* (2011) and Saqib *et al.* (2019).

Conclusion

This research documented two main outcomes. First, among the amendments examined, at lower EC_e:SAR levels (4:20, 8:40 and 12:60), the responses of sulphuric acid and gypsum were identical, but at higher level (16:80) sulphuric acid was more effective. Secondly, the disturbance in rice photosynthetic rate, stomatal conductance, transpiration rate and total chlorophyll contents due to salinity/sodicity stress were significantly overcomed with sulphuric acid treatment. Moreover, the improvement in N and K contents, K:Na ratio and biological and paddy yield were significantly consistent with the effectiveness of soil salinity/sodicity ameliorating treatment.

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Author Contributions

AAQ and GM conceptualized, AAQ investigate, statistical analyzed the data, write and prepare original draft, ZR and EAW review and edit the draft.

Conflict of Interest

Authors declare no conflict of interest.

Data Availability

The data will be made available on reasonable request to the corresponding author.

Ethics Approval

Not applicable.

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