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TECHNICAL REPORT

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Comparison of sulfurous acid generator and alternate amendments to improve the quality of saline-sodic water for sustainable rice yields

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Abstract The prolonged irrigation with marginal quality water can cause secondary salinization of soils, which necessitates for better understanding of water management alternatives. Relative performance of sulfuric acid and gypsum is still controversial to counter sodium hazards in soil/water system. As an alternative, sulfurous acid generators (SAG) are also being marketed. But up-till-now, there is not even a single field study published in scientific journals about their efficiency and economical viability for the treatment of saline-sodic water. Therefore, a field study was carried out to compare the effectiveness of SAG and alternate amendments applied on an equivalent basis to grow rice crop. SAG treatment of saline-sodic tube well water decreased only residual sodium carbonate (RSC) from 5.4 to 3.6 $\text{mmol}_c\ \text{l}^{-1}$, and had no beneficial effect on its sodium adsorption ratio (SAR) or electrical conductivity (EC). All the treatments kept soil EC and SAR around their respective threshold levels. For paddy yield, SAG, sulfuric acid, and gypsum treatments depicted nonsignificant differences. SAG and sulfuric acid treatments of water were about six times expensive than that of gypsum. It was concluded that soil-applied gypsum, to counter sodic hazards of irrigation water, is economical to sustain irrigated rice in dry regions.

Keywords Crop production · Residual sodium carbonate · Sodium adsorption ratio · Gypsum · Rice (*Oryza sativa* L.) · Economic analysis

Introduction

Under agroclimatic conditions of Pakistan, evapotranspiration is about 14–20 times higher than precipitation (GOP 2003), which is responsible for net upward movement of salts through capillary action. The shortfall in irrigation water is likely to reach 131.6 billion cubic meter (BCM) by 2013 (Ghafoor et al. 2002b). In order to supplement the canal water availability (53 BCM) at farm gate, more than 0.53 million tube wells are pumping 67.7 BCM ground water (GOP 2003). Out of this, 60–70% is hazardous owing to high electrical conductivity (EC), residual sodium carbonate (RSC), and/or sodium adsorption ratio (SAR). For evaluation of irrigation water quality, primary consideration is given to its total salt content and sodium related hazards such as SAR and RSC (Ayers and Westcot 1985; Gupta 1990; Muhammed and Ghafoor 1992; Gupta and Gupta 1997). The carbonate and bicarbonate contents of irrigation water, higher than $\text{Ca}^{2+} + \text{Mg}^{2+}$, strongly exaggerate the sodium hazards for soils and plants (Gritsenko and Gritsenko 1999). The continuous use of irrigation water having a high RSC can cause soil deterioration/sodium build up, depending upon the soil and the agroclimatic conditions (Eaton 1949; Rengasamy and Olsson 1993). In Pakistan, a safe limit of 2.5 $\text{mmo1}_c\ \text{l}^{-1}$ has been proposed for RSC by Directorate of Land Reclamation (Muhammed and Ghafoor 1992).

The sodicity hazards (SAR and/or RSC) of irrigation water can be decreased by decreasing its carbonate and bicarbonate contents, either with the addition of acids/acid formers (Doneen 1975; Miyamoto et al. 1975a; Gumaa et al. 1976; Ryan et al. 1977; Miyamoto 1977, 1998; Frenkel et al. 1978; Miyamoto and Stroehlein 1986; Gupta 1990; Ghafoor et al. 1997; Burt 1998; Griffen and Silvertooth 1999; Amrhein 2000) or by increasing the concentration of calcium with chemical amendments like gypsum (Doneen 1948; Axtell and Doneen 1949; Magadoff and Bresler 1973; Hanif et al. 1975; Kemper et al. 1975; Qureshi et al. 1975, 1977; Keisling et al. 1978; Ahmad et al. 1979; Keren and O'Connor 1982; Oster 1982; Chaudhry et al. 1984; Ghafoor et al. 1987, 2001a; Rengasamy 1987; Gupta 1990;

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Ghafoor and Zubair 1992; Malik et al. 1992; Oster 1994; Gupta and Gupta 1997; Hussain et al. 2000). Neutralization of water RSC with the use of gypsum or acid is widely recommended, although use of gypsum is highly economical and safe (Doneen 1975; Chabbra 1996; Ghafoor et al. 2001a). As gypsum has a low solubility of 0.30 g per 100 ml water at 25°C (US Salinity Lab. Staff 1954), it is possible to increase calcium (Ca^{2+}) concentration by 2–4 $mmol_c\ l^{-1}$ in flowing irrigation water (Doneen 1975; Ayers and Westcot 1985), with an expected increase in the EC of irrigation water (EC_{iw}) by 0.15–0.30 $dS\ m^{-1}$ (Oster et al. 1992). However, low dissolution rate of gypsum is considered an additional advantage to sustain long-term availability of calcium (Doneen 1975), and electrolyte concentration, to maintain the hydraulic conductivity and the structure of soils (Reeve and Doering 1966; Jurinack et al. 1984; Ayers and Westcot 1985; Rengasamy and Olsson 1993). The use of mineral acids has been found five to seven times expensive than that of gypsum (Agarwal et al. 1982; Abrol et al. 1988; Ghafoor and Muhammed 1981, 1986, 2001a, 2002) and its handling is also difficult/dangerous. As an alternative, SAG is a recently introduced technology to treat saline-sodic/sodic waters. Sulfur (S) is burnt to produce sulfur dioxide gas (SO_2) in a chamber, which is made to dissolve in a fraction (10–15%) of tube well water to form sulfurous acid (H_2SO_3). This H_2SO_3 can neutralize carbonate (${CO_3}^{2-}$) and bicarbonate (${HCO_3}^{-}$) ions of water to affect a decrease in RSC of treated water (Doneen 1975). Theoretically, this will not benefit amelioration of water EC and SAR (Amrhein 2000).

Rafiq (1990) estimated development of surface salinity and/or sodicity on an area of about 3×10^6 ha in Pakistan, which was a result of using marginal-quality drainage and groundwater without appropriate management practices. This kind of secondary salinization/sodication of soils, in Pakistan, has necessitated for better understanding of water management alternatives. Sulfuric acid and gypsum have long been recognized for their benefits in treating high SAR/RSC waters (Miyamoto et al. 1975a; Miyamoto and Stroehlein 1986). But their relative performance is still controversial to counter the Na-hazards in soil/water system (Mace et al. 1999). As an alternative to sulfuric acid and gypsum amendments, SAG (also called sulfur burners) are being marketed. But up-till-now, there is not even a single field study published in scientific journals (except an electronic publishing by Gale et al. 2001) about its effectiveness in field trials and its economical viability, in comparison with the traditional approaches. This necessitates for field trials before entering the marketing phase of SAG. This viewpoint has also been supported by Stroehlein and Pennington (1986), in a review about the use of sulfur compounds for soil and water treatments.

Sulfuric acid is considered most efficient in neutralizing the soda and alkalinity of irrigation water (Lotovitskii and Bilai 2001). However, experimental data is lacking the effectiveness of the recently introduced SAG, which produces SO_2 to form H_2SO_3 after mixing and solubilizing in water. Moreover, economic considerations are essential for the use of acids/acid forming materials to improve soil and water quality (Fuller and Ray 1963; Alawi et al. 1980; Miyamoto and Stroehlein 1986; Ghafoor et al. 2001a). In a 6-year study, Christensen and Lyerly (1954) found the use of sulfuric acid uneconomical for the treatment of water as well as soil.

Keeping in view the above facts, an experiment was carried out to study the effectiveness and economics of SAG treatment of saline-sodic water, in comparison with traditional amendments, for rice production.

Materials and methods

A field experiment was conducted on a 0.75-ha piece of alluvial soil at Post Graduate Agricultural Research Station, University of Agriculture, Faisalabad, Pakistan during May 2001 to December 2001. The calcareous soil belonged to Rasoolpur soil series (typic Haplocambids). Tube well water used to irrigate the rice crop was saline-sodic (EC = 3.24 $dS\ m^{-1}$, SAR = 17.23, RSC = 5.44 $mmol_c\ l^{-1}$, pH = 7.8). The treatments included the following:

T_0 = all irrigations with untreated saline-sodic water from a tube well.
T_1 = all irrigations with SAG treated tube well water (T/W).
T_2 = alternate irrigation with SAG treated and untreated T/W water.
T_3 = one irrigation with SAG treated and two irrigations with untreated T/W water.
T_4 = farm manure (FM) application at 15 $t\ ha^{-1}$ before transplantation of rice crop, and irrigation with untreated T/W water.
T_5 = gypsum (agriculture grade passed through 30 mesh sieve having 70% purity) applied to soil in amounts sufficient to decrease RSC of saline-sodic water to the same level as by SAG treatment.
T_6 = sulfuric acid (H_2SO_4) applied with each irrigation in amounts sufficient to decrease RSC of saline-sodic water to the same level as by SAG treatment.

The experiment was laid out in Randomized Complete Block Design (RCBD) with three replications. Rice cv. *Basmati 2000* was transplanted in July 2001. A total of 29 irrigations (including three irrigations of fresh water from a nearby canal due to mechanical problem in SAG operation during study) were applied to each treatment plot to grow the rice crop. Each irrigation was of approximately 7.5 cm, except the first irrigation of 15 cm at the time of transplantation of nursery. There was 16.8 cm of rainfall during the period of study. Composite soil samples were drawn from 0–15 and 15–30 cm depths at the start of experiment and after harvest of the rice crop. The cultural practices, like weeding, fertilizer application, and amount of irrigation water were kept uniform for all the treatments. The nitrogenous and phosphatic fertilizers were applied as urea and diammonium phosphate at 100 and 50 $kg\ ha^{-1}$, respectively. Soil analysis (Table 1) was accomplished following the methods described by US Salinity Lab. Staff (1954).

Table 1 Properties of original soil

Soil depth (cm)	Property	Mean
00–15	pH_s	8.49
	EC_e (dS m^{-1})	3.11
	SAR	16.3
15–30	pH_s	8.45
	EC_e (dS m^{-1})	3.81
	SAR	19.4
00–30	Texture	Sandy loam
10–15	Bulk density (g cm^{-3})	1.60
20–25	Bulk density (g cm^{-3})	1.62
	Infiltration rate (cm h^{-1})	1.11

The crop was harvested at biological maturity to record the biomass and the economic yields. The data were subjected to statistical analysis by Analysis of Variance (ANOVA) technique. Duncan's Multiple Range (DMR) test was applied to evaluate the treatment differences (Steel and Torrie 1980) at 5% probability. The variable costs of all the experimental inputs and support prices of the produce were used to compute the economics through partial budgeting technique.

Results and discussion

Effect of SAG treatment on the quality of saline-sodic water

The quality of water was hazardous for irrigation (Table 2) considering the water quality criteria used in Pakistan (Muhammed and Ghafoor 1992), India (Gupta and Gupta 1997; Agarwal et al. 1982), and other countries (Ayers and Westcot 1985; Abrol et al. 1988). The continued use of such quality water for irrigation will inevitably increase the price to be paid by the farmers to sustain irrigated farming (Rengasamy and Olsson 1993). Thus a sound management strategy will be needed to tackle long-term adverse effects of sodification and salinization on agriculture and environment (Gritsenko and Gritsenko 1999). To treat such low quality irrigation water, proper rates of acids/acid formers were used to reduce carbonates and bicarbonates (Miyamoto et al. 1975a,c; Gumaa et al. 1976; Ryan et al. 1977; Finck 1982; Miyamoto and Stroehlein 1986; Whipker et al. 1996; Burt 1998; Miyamoto 1977, 1998; Griffen and Silvertooth 1999; Amrhein 2000). This treatment is considered beneficial for reducing hardness of water (Christensen and Lyerly 1954) and crusting in soils (Miyamoto 1998).

Table 2 Sulfurous acid generator treatment of tube well brackish water (20 irrigations)

Irrigation number	Water quality								
	Before SAG treatment			During SAG treatment[a]			After SAG treatment (at field entry)[b]		
	EC (dS m^{-1})	SAR	RSC (mmol l^{-1})	EC (dS m^{-1})	SAR	RSC (mmol l^{-1})	EC (dS m^{-1})	SAR	RSC (mmol l^{-1})
1	3.32	16.29	5.25	3.38	16.24	0.00	3.37	16.20	4.85
2	3.51	17.85	5.50	3.74	18.96	0.00	3.56	17.97	2.52
3	3.38	15.14	4.99	3.65	16.11	0.00	3.42	15.08	1.75
4	3.27	16.61	5.80	3.30	13.03	0.90	3.34	13.52	3.10
5	3.04	15.20	5.02	27.5	15.17	0.00	3.13	15.97	4.35
7	3.30	16.38	5.50	10.4	16.70	0.00	3.31	16.55	4.36
8	3.41	18.65	5.70	3.42	18.80	0.00	3.58	19.61	3.18
9	3.58	18.57	7.00	9.68	18.15	0.00	3.65	18.92	3.40
11	3.41	15.49	6.30	5.05	15.82	0.00	3.71	17.58	3.80
12	3.11	16.06	6.40	12.1	15.88	0.00	3.18	16.50	3.40
13	3.11	17.67	5.70	5.85	15.39	0.00	3.10	16.44	3.70
14	3.06	15.75	7.50	6.24	na[c]	0.00	3.09	15.52	4.50
16	3.02	14.70	5.90	3.16	na	0.00	3.02	13.63	4.90
17	3.15	18.76	4.70	7.43	15.90	0.00	3.35	16.55	2.10
18	3.23	15.92	5.70	3.32	16.61	0.00	3.29	16.34	4.00
20	2.99	17.67	5.70	3.45	17.33	0.00	2.98	15.94	4.00
22	3.11	17.41	5.50	4.38	15.98	0.00	3.06	18.23	4.45
24	3.09	18.51	5.60	6.14	16.03	0.00	3.08	17.70	4.55
25	3.19	19.73	3.50	4.14	17.26	0.00	3.25	20.15	4.00
26	3.16	19.52	4.00	3.83	17.41	0.00	3.29	18.93	2.15
Mean	3.22	17.09	5.56	6.51	16.49	0.05	3.29	16.87	3.65
Variation over original (%)				101.9	−3.5	−99.2	2.05	−1.33	−34.4

[a] Water samples collected at SAG outlet, as SAG was able to uptake and reclaim only a portion of untreated water

[b] Water samples collected after mixing SAG-treated water (10–15%) with the rest of untreated water (85–90%), before its entry to the field

[c] Data not available

The data (Table 2) indicate that SAG treatment of saline-sodic water did not decrease its EC, rather there was an increase of 2.05%. Various studies about the treatment of irrigation water with mineral acids also support these findings (Miyamoto et al. 1975b; Miyamoto and Stroehlein 1986; Stroehlein and Pennington 1986). Miyamoto (1998) asserted that acids or acidic gas applications to irrigation water are used to prevent an increase in sodicity of irrigation water or a reduction in salinity associated with the precipitation of Ca^{2+} and $HCO_3{}^{-1}$. However, Doneen (1975) asserted that in neutralizing the bicarbonate ions of irrigation water, the total concentration (EC) does not change but merely shifts from $HCO_3{}^{-1}$ to $SO_4{}^{-2}$ form. Moreover, occasional pH tests of SAG-treated water (data not given) indicated a reduction from 7.8 to 6.8 (12.8%), which may be attributed to the negligible buffering capacity of irrigation water (Doneen 1975; Miyamoto and Stroehlein 1986; Miyamoto 1998). Several researchers in field (Christensen and Lyerly 1954; Griffen and Silvertooth 1999), green-house (Thorne 1944), laboratory (Gumaa et al. 1976; Miyamoto and Stroehlein 1986), pot (Aldrich and Turrell 1950), and simulated trials (Miyamoto 1977) have demonstrated desired reduction in pH of irrigation water with the use of sulfuric acid. It is important to recognize that the pH of acid-treated water depends not only on the acid rate relative to the alkalinity, but also on the CO_2 exchange between water and a surrounding gaseous phase (Miyamoto 1998). If acid is applied to open, aerated streams (at a rate less than about 90% of the alkalinity), it is unlikely to cause acidity-related problems. However, if the same rate of acid is applied to waters flowing through pipes, the resulting low pH may cause pipe corrosion (Miyamoto 1977). In actuality, hydrogen ions react with carbonate species, primarily $HCO_3{}^{-1}$ present in alkali (saline-sodic/sodic) irrigation water, and convert them to carbonic acid. Under a system open to the atmosphere, carbonic acid decomposes to CO_2 and H_2O. The pH of the water remains above neutral, until about 90% of the $HCO_3{}^{-1}$ ions present are converted to H_2CO_3, and eventually to CO_2 and H_2O (Miyamoto et al. 1975c). The concentration of H_2CO_3 in an open system is largely fixed by the partial pressure of CO_2. Under a closed system, which may exist in water flowing through water-filled pipes or tubes, carbonic acid (H_2CO_3) accumulates in the system. This causes the pH of the water to drop below neutral, even when the acid application is as low as 10% of the concentration of $HCO_3{}^{-1}$ (Miyamoto et al. 1975c).

SAG treatment did not cause any significant decrease in SARof irrigation water (SAR_{iw}). The nominal decrease (1.3%) in SAR_{iw} might be due to an analytical error or negligible improvement in the concentration of Ca^{2+} present in irrigation water (Lotovitski and Bilai 2001), and/or release of Ca^{2+} from silt/clay particles suspended in pumped water, after the acid treatment (Amrhein 2000). The results are also supported by a review work of Miyamoto and Stroehlein (1986), who concluded that when irrigation water contains $CaCO_3$, i.e. surface waters with calcareous sediments, the acid-treated water solubilizes Ca^{2+}, thus causing SAR to decrease. In a study, Miyamoto et al. (1975c) concluded that after addition of acid to irrigation water, there was reduction in its SAR, which showed that calcium would tend to remain in solution rather than precipitating out as $CaCO_3$. At an acid application rate of 3 me l^{-1} for the treatment of irrigation water, Miyamoto (1977) concluded that such a practice would reduce the sodicity of irrigation water characterized by SAR, as it prevents calcium precipitation or dissolves $CaCO_3$. Moreover, in this type of practice, the effect of acid on SAR will depend not only on the acid rate relative to the alkalinity, but also to a large extent upon the degree of CO_2 release into the atmosphere before acid-treated water infiltrates into soil. Our findings are further supported by the research work of Lotovitskii and Bilai (2001), who reported that acidification of irrigation water affects not only the concentration of $CO_3{}^{-2}$ and $HCO_3{}^{-1}$, but to a certain extent, the water chemistry as a whole. This is mainly caused by substitution reactions between salts of the acid and those dissolved in water. According to the authors, in the first few minutes after treatment with sulfuric acid, the concentration of sodium and chloride ions became unstable and decreased by 5–15%. However, both the ions almost recovered their initial values. Such treatment neutralized $CO_3{}^{-2}$ completely, reduced $HCO_3{}^{-1}$ content by 15–25%, and increased sulfate content and total dissolved solids by 6–12% and 0.1–0.2 g l^{-1}, respectively.

Although SAG treatment of saline-sodic water decreased its RSC from 5.56 to 3.65 mmol l^{-1} (34.4%) at filed inlet but still it was higher compared to threshold limit of 2.5 $mmol_c$ l^{-1}, which is mostly considered the maximum upper limit for safe irrigation (Wilcox et al. 1954; US Salinity Lab. Staff 1954; Ayers and Westcot 1985; Muhammed and Ghafoor 1992; Gupta and Gupta 1997). This level of RSC is expected to create infiltration problems in fine textured soils (Frenkel et al. 1978; Gupta and Gupta 1997), and nutrient disorders in crops (Ayers and Westcot 1985; Miyamoto 1998; Grattan and Grieve 1999). The authors of this paper are of the view that, in this study, safe level of RSC could only be achieved with installation of two SAG units. But following the advice of SAG manufacturing company officials, only one SAG unit was installed. The officials were of the view that the supplied SAG unit (imported from USA to accomplish this study) could easily bring down the RSC of irrigation water (5.56 $mmol_c$ l^{-1}), at the experimental site, within safe limits. The officials of SAG manufacturing company, in this country, are still recommending the installation of one SAG unit for the treatment of even higher RSC water than that used in present study. However, during the course of study, these recommendations seem to be erroneous.

Our results are in line with electronically published data of Gale et al. (2001), who in a level basin irrigation study monitored the efficiency of SAG. In the study, pH was the only property of water that was significantly affected. In this unpublished work (available at Utah State University, USA website), there was 7.5% decrease in pH, 0.96% increase in Na^{+}, 4.6% increase in $Ca^{2+} + Mg^{2+}$, 8.0% decrease in $HCO_3{}^{-1}$, and 4.2% decrease in SAR. The low efficiency of SAG was attributed to its ability of intake for dissolution of SO_2, which was only about 10–15% (if operated at full capacity) of the water flowing through water channel, and mixing that treated portion into rest of 85–90% untreated portions. Moreover, low efficiency of SAG may also be attributed to low solubility of SO_2 in irrigation water (Cotton and Wilkinson 1967; Miyamoto et al. 1975b). Large quantities of sulfur dioxide fumes were seen coming out of the sulfur-burning chamber of SAG during its operations that clearly advocate less SO_2 solubility. Our results are also supported by the research findings of Miyamoto et al. (1975a,b,c), and Miyamoto and Stroehlein (1986), who concluded that sulfuric acid treatment of irrigation water increases its electrolyte contents (EC), reduces partially/completely its carbonate and bicarbonate contents, and decreases its SAR.

Contrary to the claims of SAG manufacturing company (Sweet Water International, USA) that brackish water treated with SAG may be used to reclaim saline-sodic/sodic soils successfully, the authors are of the view that SO_2 may be too insoluble to accomplish soil reclamation if added to irrigation water. Therefore, low rates of water-applied amendments should be expected only to affect water quality, and the surface soil to a little extent (Miyamoto 1998). Thus high-Na soils should generally be treated directly with amendments. Although up-till-now there is no such a relevant published study, but our viewpoint is supported (although theoretically) by Stroehlein and Pennington (1986) in their literature review about the use of sulfur compounds for soil and water treatment.

Changes in soil properties

i. *pH of saturated soil paste* (pH_s). Soil pH has a considerable impact on controlling the plant nutrients, particularly the availability of micronutrients such as Zn, Cu, Fe, and Mn (Page et al. 1990; Naidu and Rengasamy 1993). The use of saline-sodic water for irrigation without amendment application, in general, tends to increase the soil pH that impacts soil nutrient availability, rendering plants with malnutrition (Curtin and Naidu 1998; Grattan and Grieve 1999). In this study, the data (Table 3) after the harvest of rice crop depicted that there were nonsignificant differences among the treatments for 0–15 cm soil depth. The gypsum and farm manure treatments tended to maintain the soil pH_s (pH measured in saturated extract of soil) but rest of the treatments increased $pH_{s.}$ The positive role of FM to maintain soil pH_s could be attributed to the formation of carbonic acid upon the release of CO_2 during its decomposition. Cates et al. (1982) during reclamation of a calcareous saline-sodic soil, have also reported a decrease in soil pH after addition of gypsum. Failure to obtain a marked decrease in soil pH_s either by SAG treatment (T_1) or sulfuric acid (T_6), may be attributed to buffering effect of the salts present in irrigation water against hydrogen ions ($H^{\pm}$) addition (Christensen and Lyerly 1954; Miyamoto and Stroehlein 1986). Therefore, large quantities of acids/acid formers were required to cause any appreciable decrease in soil pH (Doneen 1975; Miyamoto and Stroehlein 1986; Miyamoto 1998). Presence of calcium carbonate in this calcareous soil also acted as a buffer and resisted any appreciable change in soil pH in the alkaline range (Deverel and Fujii 1990; Leoppert and Suarez 1997; Halvin et al. 2002; Anwar et al. 2004). It is uneconomical and quite impractical to drastically lower pH of calcareous soils (Havlin et al. 2002). In most of the calcareous soils, large quantities of acids or acidulants are required (Miyamoto 1998) to dissolve $CaCO_3$ from the entire root zone. (Note that it will require 10 t of H_2SO_4 per hectare, to remove $CaCO_3$ from 1 cm of soil layer containing 7.5% $CaCO_3$ by weight). Ryan et al. (1977) demonstrated that dilute H_2SO_4 even applied in excess of the buffering capacity of the irrigation water was immediately neutralized by the soil. However, it is likely that a change in soil pH would occur with continuous application of acidified water in the long term. At 15–30 cm depth, all the treatments increased soil pH_s, except soil-applied gypsum which perhaps maintained a high EC to SAR ratio at both the depths. In general, high EC to SAR ratio tends to lower pH_s and vice versa (Ayers and Westcot 1985; Abrol et al. 1988; Ghafoor et al. 2001b). Moreover, Miyamoto (1998) concluded that much-publicized effects of lowering pH of irriga-

Table 3 Changes in soil pH_s, EC_e, and SAR with SAG-treated irrigation water and other amendments before and after rice crop (average of three replications)

Treatment	Depth (0–15 cm)						Depth (15–30 cm)					
	pH_s		EC_e		SAR		pH_s		EC_e		SAR	
	Before	After	Before	After	Before	After	Before	After	Before	After	Before	After
T_0	8.47	8.60	3.29	2.76	16.64	18.82	8.43	8.64	3.77	1.67	20.64	13.90
T_1	8.37	8.61	3.93	2.27	21.07	17.88	8.40	8.69	3.62	2.12	21.85	14.50
T_2	8.50	8.69	3.21	1.93	15.21	15.68	8.37	8.72	3.63	1.74	18.61	12.61
T_3	8.48	8.68	3.41	2.16	14.59	17.25	8.40	8.64	4.00	1.63	17.86	13.09
T_4	8.55	8.57	2.19	2.32	16.11	16.43	8.48	8.68	4.59	1.80	18.58	12.39
T_5	8.56	8.58	2.47	2.60	13.49	18.04	8.64	8.63	2.93	1.73	17.04	11.61
T_6	8.48	8.62	3.28	2.52	17.09	19.22	8.39	8.51	4.12	2.02	21.06	14.21
$LSD_{0.05}$[a]	ns[b]	ns	ns	0.83[c]	6.56[c]	ns	ns	0.14[c]	ns	ns	ns	ns

[a] $LSD_{0.05}$, least significant difference at 5% probability level

[b] ns, not significant at 5% probability level by LSD

[c] Significant at 5% probability level by LSD

tion water, and resulting increase in crop performance (probably associated with better availability of some nutrients) are, however, questionable at best in most calcareous soils, unless the pH of water is well above the equilibrium pH of $CaCO_3$ systems.

ii. *Electrical conductivity*. Soil salinity (indirectly measured through EC) exerts osmotic effects on plants (Maas and Hoffman 1977; Grattan and Grieve 1999) and often causes physiological drought if the salinity levels are greater than the critical limits of the crop. EC of soil samples (EC_e) was measured in saturated paste extracts. At the start of experiment, EC_e at 0–15 and 15–30 cm soil depths was 3.1 and 3.8 dS m^{-1}, respectively. The EC_e (Table 3) decreased with all the treatments except T_4 and T_5 at 0–15 cm depth. Control plots showed maximum EC_e, which may be attributed to no treatment of soil and water. At 0–15 cm depth, there were nonsignificant differences noted for EC_e among SAG (T_1), sulfuric acid (T_6), and gypsum (T_5) treated plots. With gypsum, a slight increase in EC_e has also been reported by Hussain et al. (1981) in a field trial. The increase in EC_e with FM might be due to accumulation of salts after mineralization of organic matter (Hao and Chang 2003).

The researchers (Hao and Chang 2003) noted a significant increase in soil EC_e due to increased levels of soluble Na^+, K^+, Mg^{2+}, Cl^-, and $HCO_3{}^-$ after 5, 10, 15, 20 and 25 years of continuous manure application at 0, 60, 120 and 180 t ha^{-1} under both irrigated and nonirrigated conditions. The researchers further estimated an annual increase in EC_e (0–1.5 m soil depth) by 0.1108 dS m^{-1} for every ton of salt applied through the cattle manure under nonirrigated conditions. At 15–30 cm depth, nonsignificant differences were observed among all the treatment plots regarding this important soil parameter. At lower depth decrease in EC_e of control plots might be due to accumulation of salts in the top layer. This might be due to a decrease in permeability of the surface layer (0–15 cm) as no source of calcium (to favor sustainability in infiltration rate) was applied. The observed values of EC_e at both the depths were still below the critical level of 4 dS m^{-1} (US Salinity Lab. Staff 1954; Ayers and Westcot 1985; Gupta and Gupta 1997) by all the treatments under investigation in this well drained, moderately coarse textured and moderately calcareous soil. This could be attributed to high leaching fraction (LF) achieved, (Chang et al. 1982) as the rice crop was grown with 29 irrigations.

iii. *Sodium adsorption ratio*. Water and soil sodicity are expressed in terms of SAR, with high SAR values having the potential for deterioration in soil structure, low infiltration rate, specific-ion effect, and deficiencies of several essential nutrients. At the start of experiment, some plots were slightly Na-affected (Table 4), which on the average tended to keep the soil SAR greater than 15, a critical limit for sodic soils (US Salinity Lab. Staff 1954; Ayers and Westcot 1985). For soil SAR, there was nonsignificant difference for all the treatments at both the depths (Table 3). Actually a steady-state condition was developed after a huge number of irrigations (29) to grow rice crop. Especially the case was true for 0–15 cm soil depth where the soil SAR was maintained well around irrigation water SAR, i.e. 17.1. After the harvest of the rice crop similar effectiveness (nonsignificant treatment differences) of acid and gypsum treatments for soil SAR have also been reported by Cate et al. (1982), which were attributed to very low initial soil ESP.

Table 4 Sodium (Na^+) concentration (me l^{-1}) in soil at start of the experiment

Treatment	Mean	
	Depth (0–15 cm)	Depth (15–30 cm)
T_0	25.76	32.12
T_1	34.78	35.94
T_2	23.08	26.65
T_3	21.23	29.67
T_4	18.48	26.62
T_5	22.35	26.34
T_6	26.38	33.70

At 0–15 cm depth, the expected steady-state increase in soil SAR with gypsum, and relatively better role of acid treatments, might be due to low rates of gypsum dissolution. The results are in line with those of Alawi et al. (1980), who pointed out that when soil-applied gypsum is used at very low rates, the effects are minor and short-lasting, and thus sulfuric acid is superior to the gypsum treatment. For 15–30 cm soil layer, our results are similar with those of Chaudhry et al. (1989), who reported that SAR in all plots significantly decreased with nonsignificant differences among control, gypsum at 50% soil gypsum requirement (SGR), and sulfuric acid at 50% SGR treatments, after growing four rice and four wheat crops.

In the current study, observed values of soil SAR at both the depths have been maintained around the critical level of 13 (especially for 15–30 cm soil layer) by all the treatments under investigation in this well drained, moderately coarse textured, and moderately calcareous soil. However, for fine textured soils, with low infiltration rates, and/or noncalcareous soils, to expect similar behavior might be premature, for which additional long-term studies are imperative. Moreover, potential danger of soil sodication as a result of the application of high sulfate irrigation water has been reported. This might be due to the fact that $SO_4{}^{-2}$ ions in excess of $Ca^{\pm 2}$, may result in Ca-desorption from the colloidal complex to maintain the steady equilibrium between adsorbed and solution calcium (Eaton 1954; Dutt and Doneen 1963; Miyamoto 1977; Cerda et al. 1979; Chabbra 1996; Javid and Ali 1999).

Paddy yield

The results for paddy yield (Table 5) reveal that effects of all the treatments on EC_e, SAR, and pH_s were comparable in favor of soil and crop health, and their productivity. As all

Table 5 Effect of SAG and other treatments of irrigation water on straw and paddy yields (average of three replications)

Treatments	No. of tillers (m^2)	1,000–grain weight (g)	Straw yield (kg ha^{-1})	Paddy yield (kg ha^{-1})
T_0	163	20.87	2,845	1,357
T_1	166	21.12	4,647	2,354
T_2	162	20.46	3,913	2,048
T_3	173	21.04	4,723	2,434
T_4	195	21.45	5,136	2,660
T_5	174	21.52	4,115	2,237
T_6	185	21.65	4,708	2,339
$LSD_{0.05}$[a]	ns[b]	0.802[c]	1,566[c]	532.1[c]

[a] $LSD_{0.05}$, least significant difference at 5% probability level

[b] ns, not significant at 5% probability level by LSD

[c] Significant at 5% probability level by LSD

the three soil quality parameters were maintained around their respective threshold values for rice crop (Mass and Hoffman 1977), therefore, nonsignificant and/or minor differences have been recorded for paddy yield among acid and gypsum-treated plots. The yield pattern for rice crop seems to be in line with those of Overstreet et al. (1951), who applied gypsum, sulfuric acid, and sulfur in the equivalent amounts to reclaim a salt-affected soil of the *Fresno* series. Significantly higher pasture yields were reported for sulfuric acid treated plots than that for gypsum treated ones, during initial years. However, 20 months after the application of treatments, there was nonsignificant difference between yields of H_2SO_4, and gypsum-treated plots. Similar results were obtained by Chaudhry et al. (1989) for first rice crop grown during *kharif* season in 1982. An increase in yield over control plots, with the addition of sulfuric acid have also also been reported by Cate et al. (1982) in a field study during reclamation of a calcareous saline-sodic soil. Yasin et al. (1998) have also reported maximum paddy yield with acid treatment, closely followed by gypsum, and minimum paddy and straw yield from the control plots. A better crop growth with the use of sulfuric acid on normal, calcareous soils has been demonstrated in several studies, and is generally attributed to better availability of some nutrients (Ryan et al. 1975a,b; Ryan and Stroehlein 1979; Miyamoto 1998). In a field study by Chapman (1980), an increase in paddy yield (16%) with sulfuric acid treatment over gypsum has been reported, which was attributed to increased availability of some nutrients due to instantaneous reaction of sulfuric acid with the soil (Havlin et al. 2002).

Economic analysis

Economic considerations are essential regarding the use of amendments for the improvement of soil and water quality (Fuller and Ray 1963; Alawi et al. 1980; Ayers and Westcot 1985; Chabbra 1996). Several researchers in Pakistan (Ghafoor and Muhammed 1981; Ghafoor et al. 1986, 1997, 1998, 2001a; Bhatti 1986; Chaudhry et al. 1989), India (Yadav 1973; Chabbra 1996), and other countries of the world (Christensen and Lyerly 1954; Doneen 1975; Havlin et al. 2002) have reported sulfuric acid application to soil or water uneconomical and several times expensive than that of gypsum. However, economic analysis about the use of H_2SO_4 have never been reported in several studies (Throne 1944;

Table 6 Economics of SAG and other treatments of saline-sodic water for rice crop (US $[a] ha^{-1})

Treatment	Total income (US $ ha^{-1})	Variable expenses (US $ ha^{-1})					Net benefit (US $ ha^{-1})
		Sulfur	Petrol	SAG depreciation	Other	Total	
T_0	261	–	–	–	–	–	261
T_1	444	57.17	94.32	174.68	–	326	118
T_2	388	28.58	47.15	87.33	–	163	225
T_3	459	19.05	31.43	58.23	–	109	350
T_4	500	–	–	–	31.25	31	469
T_5	422	–	–	–	58.03	58	364
T_6	441	–	–	–	304.77	305	136

Details of economic computations: (A) Rates of variable items (US $): (1) paddy = 7.3/40 kg, (2) gypsum = 0.5/50 kg (70% pure—30 mesh), (3) petrol = 0.6/l, (4) H_2SO_4 of commercial grade = 0.28/l, (5) sulfur = 0.2/kg, (6) farm manure = 1.7/1,000 kg, (7) cost of FM spreading = 1.7 per 4 ton loader, (8) cost of gypsum broadcast = 1.7 per 20 bags a day; (B) Amounts of variable amendments; (i) To lower RSC of saline-sodic water, H_2SO_4 used during 8-month study = 1,098 l, (ii) To lower RSC of saline-sodic water, gypsum used during 8-month study = 4,970 kg; (C) Variable costs calculations for SAG; (1) Rate of sulfur burning = 13.19 kg/ha/irrigation, (2) Rate of petrol burning in SAG = 6.6 l/ha/irrigation, (3) SAG depreciation cost per hour = price of new generator/hour (0.26) + interest (14%) cost per hour (0.23) + repair cost/hour (0.22) + tech. labor cost per hour (0.31) and US $ 1.02; (3a) Purchase price of a new generator (C) = US $ 5,833, Salvage value (S) = US $ 583, SAG working hours = 20,000 h, Price of a new generator per hour = (5,833 – 583)/20,000 = US $ 0.26; (3b) Interest cost = (C + S)/2 = US $ 3208.33 (Average annual investment), Actual annual interest cost = 3208.33 × 0.14 = US $ 449.17, Interest cost per hour = 449.17/2,000 (working hours) = US $ 0.23; (3c) Annual repair/spare parts cost = US $ 433.33, Repair cost per hour = 433.33/2,000 = US $ 0.22; (3d) Technical labor cost per hour = US $ 2.50/day of 8 h = US $ 0.31; (4) SAG dep. cost/ha/irrigation = 1.02 × 6.61 (hours to irrigate 1 ha) = US $ 6.74

[a] US $ 1.00 = Pak Rs 60.00

Overstreet et al. 1951, 1955; Mathers 1970; Miyamoto et al. 1975a,b,c; Ryan et al. 1975a,b; Miyamoto 1977, 1998; Chand et al. 1977; Prather et al. 1978; Wallace and Muller 1978; Ryan and Stroehlein 1979; Ashraf 1979; Chapman 1980; Nadeem 1981; Mian and Baig 1982; Miyamoto and Stroehlein 1986; Akram et al. 1989; Mace et al. 1999; Peterson 2000; Gale et al. 2001; Amezketa 2005).

For the present study, economics was computed (Table 6) by using the partial budgeting method. We differentiated the economic analysis into two components consisting of (1) total variable cost per unit area (US \$ ha^{-1}), i.e. the cost(s) that varied from treatment to treatment, excluding the costs which were uniform for all the treatments, and (2) gross income per unit area (US \$ ha^{-1}) received from each treatment. The gross income was tabulated from the support price of paddy. The net benefit (B_{net}) was tabulated as the difference between the gross benefit (B_{g}) and variable cost(s) (V_{c}) for each treatment as given in Eq. (1).

$$B_{\text{net}} = B_{\text{g}} - V_{\text{c}} \tag{1}$$

Assuming SAG life of 10 years with 20,000 working hours, capital and maintenance costs of SAG were computed for 8-month study period and thus variable costs were computed accordingly for each of the three SAG treatments.

Maximum total variable cost was incurred on T_1, followed by T_6, T_2, T_3, T_5, and T_4 while there was no cost on control treatment (T_0). Total gross benefit was the highest with T_4, followed by T_5, T_3, T_0, T_2, T_6, and T_1. For sustainable paddy yield, analysis results favor the use of organic matter and gypsum to counter the sodicity hazards of irrigation water. The use of SAG and sulfuric acid was around six times expensive than that of gypsum. Similar results have been reported by Chaudhry et al. (1989), where on economic grounds, gypsum application at 100% gypsum requirement was found most economical, although maximum paddy and wheat grain yields, were obtained with H_2SO_4 applied at 50% soil gypsum requirement. Similarly, Christensen and Lyerly (1954) in a 6-year study found the use of sulfuric acid uneconomical for the treatment of water as well as soil. Doneen (1975) discussed usefulness of various amendments to improve the quality of irrigation water (especially with salt contents less than 10 me l^{-1}) and concluded gypsum as the most economical ameliorant.

Conclusions

SAG treatment of saline-sodic water reduces RSC by 34%, which is still higher than the safe limit of 2.5 $\text{mmol}_\text{c}\ \text{l}^{-1}$. The poor performance of SAG may be attributed to its low intake of flowing water, i.e. only 10–15% portion for treatment, as well as to the low solubility of SO_2 in water. There is a need for some engineering modifications in the design of SAG. At statistically similar yield levels, the use of SAG as well as sulfuric acid was about six times expensive than that of gypsum. The results of this study help to opine that to grow rice crop in well-drained soils, waters with SAR and RSC higher than critical levels can be successfully used, and the rate of amendments applied could be decreased to make the soil-water-crop production system cost-effective. Economic analysis clearly favors the use of gypsum to counter the sodicity hazards of irrigation water for sustainable yields of rice crop on moderately coarse textured, moderately calcareous soils, in dry regions. However, for fine textured soils with low infiltration rates and/or noncalcareous soils, to expect similar response might be premature, for which long-term studies are imperative.

References

Abrol IP, Yadav JSP, Masoud FI (1988) Salt-affected soils and their management. Soil Bull 39:99–110

Agarwal RR, Yadav JSP, Gupta RN (1982) Saline and alkali soils of India. ICAR, New Delhi, India, pp 223–249

Ahmad B, Kemper WD, Haider G, Niazi MAK (1979) Use of gypsum stones to lower the SAR of irrigation water. Soil Sci Soc Am J 43:698–702

Akram M, Hasan G, Ashraf M, Chaudhry E (1989) Effect of gypsum and sulfuric acid on soil properties and dry matter yield of wheat grown in a highly saline-sodic soil. J Agric Res 27(2):113–119

Alawi BJ, Stroehlein JL, Hanlon EA Jr, Turner F Jr (1980) Quality of irrigation water and effects of sulfuric acid and gypsum on soil properties and Sudan grass yields. Soil Sci 129(5):315–319

Aldrich DG, Turrell FM (1950) Effect of soil acidification on some chemical properties of a soil and plants grown thereon. Soil Sci 70:83–90

Amezketa E, Aragüés R, Gazol R (2005) Efficiency of sulfuric acid, mined gypsum and two gypsum by-products in soil crusting prevention and sodic soil reclamation. Agron J 97:983–989

Amrhein C (2000) Revisiting acid injection into irrigation water. Golf Course Management

Anwar SA, Ibrahim M, Ishaq M, Ahmad N (2004) Use of sulfuric acid on normal calcareous soils. In: Abstracts 10th International Congress of Soil Science Society of Pakistan, Tandojam, Pakistan

Ashraf MM (1979) Effect of sulphuric acid and super phosphate on the chemical properties of saline sodic soil in relation to rice production. MSc Thesis, Department of Soil Science, University of Agriculture Faisalabad, Pakistan

Axtell JD, Doneen LD (1949) The use of gypsum in irrigation water. Better Crops Plant Food 33(9):16–23

Ayers RS, Westcot DW (1985) Water quality for agriculture. Irrigation and drainage paper 29. FAO, Rome, Italy, p 174

Bauder JW, Brock TA (2001) Irrigation water quality, soil amendment, and crop effects on sodium leaching. Arid Land Res Manag 15:101–113

Bhatti HM (1986) Management of irrigation water qualities for crop production. Final Tech. Report of PL-480 Project, Ayub Agriculture Research Institute, Faisalabad, Pakistan

Burt CM (1998) Chemicals for fertigation. In: Proc. International Irrigation Show, IA's 19th Annual Conference ITRC paper 98–002, San Deigo, California, USA

Cates RL, Haby VA Jr, Skogley EO, Ferguson H (1982) Effectiveness of by-product sulfuric acid for reclaiming calcareous, saline-sodic soils. J Environ Qual 11:299–302

Cerda A, Fernandez FG, Caro M, Guillen MG (1979) Growth and mineral composition of two lemon varieties irrigated with saline waters. Agrochimica 23:387–396

Chabbra RC (1996) Soil salinity and water quality. Oxford & IBH, Bombay, India, pp. 205–237

Chand M, Abrol JP, Bhumbla DR (1977) A comparison of the effect of eight amendments on soil properties and crop growth in highly sodic soil. Indian J Agric Sci 47(7):348–54

Chang C, Dubetz S, Sommerfeldt TG, MacKay DC (1982) Leaching fractions and salt status of two irrigated gypsum rich soils in Southern Alberta. Can J Soil Sci 62:97–103

Chapman (1980) Effect of sulfur, sulfuric acid and gypsum on the rice grain yield of bluebonnet and IR661. Aus J Exp Agric Anim Husbandry 20:724–730

Chaudhry MR, Hamid A, Javid MA (1984) Use of gypsum in amending sodic water for crop production. Pub. No.136, Mona Rec. Expt. Proj. WAPDA colony, Bhalwal, Sargodha, Pakistan, p 23

Chaudhry MR, Ihsannullah, Ahmad CB (1989) Reclamation of moderately salt-affected soil with sulphuric acid and gypsum. Pak J Agric Res 10(3):279–288

Christensen PD, Lyerly PJ (1954) Yields of cotton and other crops as affected by application of sulfuric acid in irrigation water. Soil Sci Soc Am Proc 18:433–436

Christians N (1999) Why inject acid into irrigation water? Golf Course Management 67(6):52–56

Cotton FA, Wilkinson GFRS (1967) Nontransition elements. Advanced inorganic chemistry, a comprehensive text, 2nd edn. Interscience Publishers, New York, pp 540–543

Curtin D, Naidu R (1998) Fertility constraints to plant production. In: Sumner ME, Naidu R (eds) Sodic soil: distribution, management and environmental consequences. Oxford University Press, New York, USA, pp 107–123

Deverel SJ, Fujii R (1990) Chemistry of trace elements in soils and ground water. In: Tanji KK (ed) Agricultural salinity assessment and management. ASCE, New York, USA, pp 64–90

Doneen LD (1948) The quality of irrigation water and soil permeability. Soil Sci Soc Am Proc 13:523–526

Doneen LD (1975) Water Quality for Irrigated Agriculture. In Poljakoff-Mayber A, Gale J (eds) Plants in saline environments. Springer, Berlin Heidelberg New York, pp 56–75

Dutt GR, Doneen LD (1963) Predicting the solute composition of the saturation extract from soil undergoing salinization. Soil Sci Soc Am Proc 27:627–630

Eaton FM (1949) Significance of carbonates in irrigation waters. Soil Science 60:123–133

Eaton FM (1954) Formulas for estimating leaching and gypsum requirements of irrigation waters. Texas Agric Expt Sta Misc Pub 111, pp 1–18

Fink A (1982) Fertilizers and fertilization. Verlog Chimic, Weinheim

Frenkel H, Goertzen JO, Rhoades JD (1978) Effects of clay type and content, ESP, and electrolyte concentration on clay dispersion and soil hydraulic conductivity. Soil Sci Soc Am J 42:32–39

Fuller WH, Ray HE (1963) Gypsum and sulfur-bearing amendments for Arizona soils. Ariz Agric Exp Stn Bull A-27, p 38

Gale G, Koenig R, Barnhill J (2001) Managing soil pH in Utah. Utah State University Extension Electronic Publishing, Logan, UT

Ghafoor A, Chaudhry MR, Qadir M, Murtaza G, Ahmad HR (1997) Use of agricultural drainage water for crops on normal and salt-affected soils without disturbing biosphere equilibrium. Pub no. 176, IWASRI, Lahore, Pakistan, p 135

Ghafoor A, Muhammed S (1981) Comparison of H_2SO_4, HCl, HNO_3, and gypsum for reclaiming calcareous saline-sodic soil and for plant growth. In Bull. (J.) Irrigation, Drainage and Flood Control Research Council of Pakistan, 11:69–75

Ghafoor A, Muhammed S, Mujtaba G (1986) Comparison of gypsum, H_2SO_4, HCl, and $CaCl_2$ for reclaiming subsoiled calcareous saline-sodic Khurrianwala soil series. J Agric Res 24:179–183

Ghafoor A, Muhammed S, Yaqub M (1987) Use of saline-sodic water for reclamation of salt-affected soil and for crop production. Pak J Soil Sci 2:17–21

Ghafoor A, Murtaza G, Qadir M (2001a) Gypsum: an economical amendment for amelioration of saline-sodic waters and soils for improving crop yield. National Workshop on Agricultural Use of Gypsum. LRRI, NARC, PARC, Islamabad, Pakistan

Ghafoor A, Murtaza G, Qadir M (2002a) Problems and treatment of low quality water for agriculture under arid and semi-arid conditions. In: Azam F et al. (eds) Technologies for sustainable agriculture. NIAB, Faisalabad, Pakistan, pp 107–116

Ghafoor A, Nadeem SM, Hassan A, Sadiq M (2001b) Reclamation response of different textured saline-sodic soils to ECiw:SARiw. Pak J Soil Sci 19:92–99

Ghafoor A, Qadir M, Murtaza G (2002b) Agriculture in the Indus plains: sustainability of land and water resources: a review. Int J Agric Biol 4(3):428–437

Ghafoor A, Qadir M, Murtaza G, Ahmad HR (1998) Strategies to harvest sustainable rice and wheat yields using brackish water for irrigation. J Arid Land Stud 7S:165–169

Ghafoor A, Zubair M (1992) Solubility of different gypsum size-grades in synthetic saline-sodic waters. Pak J Agric Sci 29:69–73

GOP (2003) Economic survey of Pakistan. Economic Advisor's Wing, Finance Div., GOP, Islamabad, Pakistan

Grattan SR, Grieve CM (1999) Salinity-mineral nutrient relations in horticultural crops. Sci Hortic 78:127–157

Griffen JR, Silverttoth JC (1999) Evaluation of an acid soil conditioner in an irrigated cotton production system. Arizona Cotton Report Series, pp 260–274

Gritsenko GV, Gritsenko AV (1999) Quality of irrigation water and outlook for phytomelioration of soils. Eurasian Soil Sci 32(2):236–242

Gumaa GS, Prather RJ, Miyamoto S (1976) Effect of sulfuric acid on sodium-hazard of irrigation water. Plant Soil 44:715–721

Gupta IC (1990) Use of saline water in agriculture. Oxford & IBH, Bombay, India, p 307

Gupta SK, Gupta IC (1997) Management of saline soils and waters. Scientific Publishers, Jodhpur, India, pp 71–98

Halvin JL, Beaton J, Tisdale SL, Nelson WL (2002) Soil acidity and alkalinity, in soil fertility and fertilizers; an introduction to nutrient management, 6th edn. Prentice Hall, NJ

Hanif M, Qureshi RH, Rajoka MI, Sandhu GR (1975) Use of saline-sodic water for crop production. I. Effect of amended and un-amended saline-sodic water on the growth of maize and properties of a normal loam soil. The Nucleus 12:39–42

Hao X, Chang C (2003) Does long-term heavy cattle manure application increases salinity of a clay loam soil in semi-arid Southern Alberta. Agric Ecosyst Environ 94:89–103

Hussain G, Sadiq M, Hamid A, Ali H (1981) Determination of suitable dose of gypsum in relation to quality of irrigation waters. Mona Reclamation Experimental Project, pub. no. 112, WAPDA, Bhalwal, Pakistan, p 23

Hussain N, Arshad M, Salim M, Ali A (2000) Sodic water management with gypsum application for sustainable crop production. Pak J Biol Sci 3:996–997

Imas P (2000) Integrated nutrient management for sustaining crop yields in calcareous soils. GAU-PRII-IPI Nat. Symposium balanced nutrition of ground nut and other field crops grown in calcareous soils of India, Junagadh, India

Javid MA, Ali ChK (1999) Soil sodification as a function of high sulphate irrigation water application, In: Proc. National workshop on water resources achievements and issues in 20th century and challenges for the next millennium. Islamabad, Pakistan, pp 228–234

Jurinack JJ, Amrhein C, Wagenet RJ (1984) Sodic hazard: the effect of SAR, salinity on soils and over-burden materials. Soil Sci 137:152–159

Keisling TC, Rao PSC, Jessup RE (1978) Gypsum dissolution and sodic soil reclamation as affected by water flow velocity. Soil Sci Soc Am J 42:726–732

Kemper WD, Olson J, DeMooy CJ (1975) Dissolution rate of gypsum in flowing water. Soil Sci Soc Am Proc 39:458–463

Keren R, O'Connor GAO (1982) Gypsum dissolution and sodic soil reclamation as affected by water flow velocity. Soil Sci Soc Am J 46:726–732

Loeppert RH, Suarez DL (1997) Carbonate and Gypsum. In: Page AL (ed) Method of soil analysis. Part 3. SSSA Book Ser. 5. SSSA, Madison, WI, pp 437–474

Lotovitskii PS, Bilai VA (2001) Effect of chemical ameliorants on the chemistry of surface water used for irrigation. Water Res 28(4):451–460

Mace JE, Amrhein C, Oster JD (1999) Comparison of gypsum and sulfuric acid for sodic soil reclamation. Arid Soil Res Rehabil 3:171–188

Magadoff F, Bresler E (1973) Physical aspects of soil water and salt in ecosystems. In: Hadas A, Swartzendruber D, Rijtema PE, Fuchs M, Yaron B (eds) Ecological studies. analysis and synthesis, vol 4. Springer, Berlin Heidelberg New York, pp 441–452

Malik D, Hussain G, Sherazi SJA (1992) On-farm evaluation of gypsum application and its economics. In: Soil health for sustainable agriculture. Proceedings of the 3rd National Congress of Soil Sciences, , Lahore, Pakistan, pp 407–420

Mass EV, Hoffman GJ (1977) Crop salt tolerance: current assessment. J Irrig Drain Div ASCE 103(IR):115–134

Mathers AC (1970) Effect of ferrous sulfate and sulfuric acid on grain sorghum yields. Agron J 62:555–556

Mian MA, Baig MA (1982) Application of sulphur and sulphuric acid and the availability of plant nutrients and chemical composition of maize. Pak J Agric Sci 19(3/4):154–160

Miyamoto S (1977) Predicting effects of sulfuric acid on qualities of irrigation and drainage waters in calcareous soils. J Environ Qual 6(1):12–18

Miyamoto S (1998) Use of acids and acidulants on alkali soils and water. In: Wallace A, Terry RE (eds) Handbook of soil conditioners. Marcel Dekker, Madison, NY, pp 217–256

Miyamoto S, Ryan J, Stroehlein JL (1975a) Potentially beneficial use of sulfuric acid in southwestern agriculture. J Environ Qual 4:431–437

Miyamoto S, Ryan J, Stroehlein JL (1975b) Sulfuric acid for the treatment of ammoniated irrigation water: I. Reducing ammonia volatilization. Soil Sci Soc Am Proc 39:544–548

Miyamoto S, Ryan J, Stroehlein JL (1975c) Sulfuric acid for controlling calcite precipitation. Soil Sci 120:264–271

Miyamoto S, Stroehlein JL (1986) Sulfuric acid effects on water infiltration and chemical properties of alkaline soils and water. Trans ASAE 29(5):1288–1296

Muhammed S, Ghafoor A (1992) Irrigation water salinity/sodicity analysis. In: Haider G (ed) Manual of soil salinity research. Publ no. 147, IWASRI, Lahore, Pakistan, pp 3.1–3.28

Nadeem MT (1981) Response of rice crop to sulphuric acid. MSc Thesis, Department of Soil Science, University of Agriculture Faisalabad, Pakistan

Naidu R, Rengasamy P (1993) Ion interactions and constraints to plant nutrition in Australian sodic soils. Aus J Soil Res 31:801–819

Norton ER, Silvertooth JC (2001) N Volatilization from Arizona irrigation waters. Arizona Cotton, Univ Ariz Coll of Agric and Life Sci, Report no. 1224, University of Arizona, Tucson, AZ

Oster JD, Singer MJ, Fulton A, Richardson W, Prichard T (1992) Water penetration problems in California soils: prevention, diagnosis and solutions. Kearney Foundation of Soil Science DANR, University of California, USA, p 165

Oster JD (1982) Gypsum usage in irrigated agriculture: a review. Fert Res 3:73–89

Oster JD (1994) Irrigation with poor quality water. Agric Water Manag 25:271–97

Overstreet R, Martin JC, King HM (1951) Gypsum, sulfur, and sulfuric acid for reclaiming an alkali soil of the Fresno series. Hilgardia 21(5):113–127

Overstreet R, Martin JC, Schulz RK, McCutcheon OD (1955) Reclamation of an alkali soil of the Hacienda series. Hilgardia 24(3):53–69

Page AL, Chang AC, Adriano DC (1990) Deficiencies and toxicities of trace elements. In: Tanji KK (ed) Agricultral salinity assessment and management. ASCE, New York, USA, pp 138–160

Peterson SS (2000) Sulfuric acid and phosphoric acid as a soil amendment in alfalfa seed. Draft report submitted to the California Alfalfa Seed Production Research Board, California, USA

Prather RJ, Goertzen JO, Rhoades JD, Frenkel H (1978) Efficient amendment use in sodic soil reclamation. Soil Sci Soc Am J 42:782–786

Qureshi RH, Aslam M, Salim M, Sandhu GR (1977) Water management for agriculture. Proceedings of Seminar, Lahore, Pakistan, pp 329–36

Qureshi RH, Hanif M, Rajoka MI, Sandhu GR (1975) Use of saline-sodic water for crop production economics, In: Proc. Optimum use of water in agriculture, Cent-Scientific Programme Report no 17, Ankara, Turkey, pp 63–69

Rafiq M (1990) Soil resources and soil related problems in Pakistan. In: Ahmad et al. (eds) Soil Physics application under stress environment. Proceedings of the Symposium Applied Soil Physics in Stress Environment. Islamabad, 1989. BARD Project, PARC, Islamabad, pp 16–23

Reeve RC, Doering EJ (1966) The high salt water dilution method for reclaiming sodic soils. Soil Sci Soc Am Proc 30:498–504

Rengasamy P (1987) Importance of calcium in irrigation with saline-sodic water—a viewpoint. Agric Water Manag 12:207–219

Rengasamy P, Olsson KA (1993) Irrigation and sodicity. Aus J Soil Res 31:821–837

Ryan J, Miyamoto S, Stroehlein JL (1977) Preliminary evaluation of H_2SO_4 application methods to soils. Plant Soil 46:629–632

Ryan J, Stroehlein JL (1979) Sulfuric acid treatment of calcareous soils: effects on phosphorus solubility, inorganic phosphorus forms and plant growth. Soil Sci Soc Am J 43:731–735

Ryan J, Stroehlein JL, Miyamoto S (1975a) Effect of surface applied sulfuric acid on growth and nutrient availability of five range grasses in calcareous soils. J Range Manag 28(5):411–414

Ryan J, Stroehlein JL, Miyamoto S (1975b) Sulfuric acid application to calcareous soils: Effects on growth and chlorophyll content of common bermudagrass in the greenhouse. Agron J 67:633–637

Steel RGD, Torrie JH (1980) Principles and procedures of statistics, 2nd edn. McGraw Hill Book, NY, USA

Stroehlein JL, Pennington DA (1986) The use of sulfur compounds for soil and irrigation water treatments. In: Tabatabai MA (ed) Sulfur in agriculture, agronomy monograph 27. ASA, Madison, WI, USA, pp 435–454

Thorne DW (1944) The use of acidifying materials on calcareous soils. J Am Soc Agron 37:815–828

US Salinity Lab. Staff (1954) Diagnosis and improvement of saline and alkali soils. USDA Handbook 60, Washington, DC, USA

Wallace A, Muller RT (1978) Complete neutralization of a portion of calcareous soil as a means of preventing iron chlorosis. Agron J 70:888–890

Whipker BE, Bailey DA, Nelson PV, Fonteno WC, Hammer PA (1996) A novel approach to calculate acid additions for alkalinity control in greenhouse irrigation water. Commun Soil Sci Plant Anal 27(5–8):959–976

Wilcox LV, Blair GY, Bower CA (1954) Effect of bicarbonates on suitability of water for irrigation. Soil Sci 77:259–266

Yadav JSP (1973) Research on water management and salinity. Final Tech Report of All India Coordinated Scheme, PAU, Ludhiana, India

Yasin M, Zada R, Niazi BH (1998) Effectiveness of chemical and biotic methods for reclamation of saline-sodic soil. Pak J Soil Sci 15:179–182