STRATEGIES FOR PRODUCTIVE USE OF BRACKISH WATER FOR SUSTAINABLE FOOD GRAIN PRODUCTIUON IN DRY REGIONS[1]

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ABSTRACT

Due to unavoidable, prolonged irrigation with marginal quality water, secondary salinization of irrigated soils in Pakistan has necessitated to a need for better understanding of the water management alternatives. Although H_2SO_4 and gypsum have far been recognized for their benefits in treating brackish water but during field trials, their relative performance still remains controversial for counteracting the Na-hazards in soil/water system. As alternative sulfur burners are also being marketed but up till now there is not even a single field study published in some journal about their efficiency and economical viability for the treatment of brackish water. Therefore a field study was carried out to compare the effectiveness of sulfurous acid generator (SAG) and other water/soil applied amendments on a normal, calcareous, well drained, sandy loam soil. Rice 2001, wheat 2001-02, and rice 2002 were planted in rotation during the experimentation period with a total of 54 treated and 8 untreated irrigations (each of 7.5 cm). Tube well water used had EC = 3.24 dS m^{-1}, SAR=17.23 and RSC = 5.44 $mmol_c\ L^{-1}$. The treatments were: T_0) Brackish tube well water without any amendment; T_1) All irrigation with water passed through SAG; T_2) Alternate irrigation-one of SAG treated and one of tube well water, T_3) One irrigation with SAG treated water and two with untreated tube well water; T_4) FYM @ 15 t $ha^{-1}yr^{-1}$; T_5) Soil applied gypsum to each crop equivalent to affect a decrease in WRSC of tube well water treated with SAG, and T_6) H_2SO_4-fertigation at each irrigation equivalent to affect a decrease in RSC of tube well water with SAG. Water analysis after treatment with SAG (an average of 20 irrigations) revealed that SAG treatment affected only one parameter i.e. water RSC from 5.44 to 3.55, and had no beneficial effect on SAR_{iw} and EC_{iw}. After three crops, a minor decrease (up to 2.5%) and increase (up to 5.3%) in soil pH_s over initial values was noted at 0-15 & 15-30 cm depth. After three crops the soil EC_e and SAR were maintained below the threshold levels and the treatments had non-significant differences. On the basis of three crops, net benefit was maximum, from T_4 followed by T_5, T_3, T_0, $T_{2,}$ T_6 and T_1. The use of sulfur burner/ sulfuric acid was found to be 5 times costlier than gypsum in our study. It is concluded that soil application of gypsum and/or farmyard manure to counter the sodic hazards of irrigation water will be useful as well as economical for rice-wheat rotation on a normal, calcareous well drained soil. However, for fine textured soils with low infiltration rates, to expect similar situation might not be correct for which additional studies are imperative.

1 INTRODUCTION

Under agro-climatic conditions of Pakistan, evapo-transpiration is several times higher than rainfall (2025 and 150 mm, respectively), which is responsible for net upward movement of salts through capillary action. The shortfall in irrigation water requirement is likely to reach 107 MAF by 2013 (Ghafoor et al., 2002b). In order to supplement to present canal water availability at farm-gate (43 MAF), more than 531,000 tube wells are pumping 55 MAF in Pakistan (Anonymous, 2003), of which 60-70% is hazardous owing to high EC RSC and/or SAR. For evaluation of the irrigation water quality, primary consideration is usually made to its total salt contents and sodium related hazards (Ayers and Westcot, 1985; Gupta, 1990; Gupta and Gupta, 1997). The carbonate and bicarbonate contents of irrigation water higher than $Ca^{2+}{}_{+}Mg^{2+}$ strongly exaggerate the sodium hazards for soils and plants (Gritsenko and Gritsenko, 1999). Thus the continuous use of irrigation water containing residual sodium carbonate (RSC) causes soil deterioration in due course of time depending upon soil and agro-climatic conditions (Rengasamy and Olsson, 1993). In Pakistan, safe limit of 2.5 $mmo1_c\ L^{-1}$ for RSC has been proposed by Directorate of Land reclamation while 5.0 $mmo1_c\ L^{-1}$ by WAPDA (Muhammad and Ghafoor, 1992).

The sodicity hazards (SAR and RSC) of poor quality water could be decreased by increasing calcium through addition of chemical amendments like gypsum, calcium chloride etc (Gupta, 1990; Gupta and Gupta, 1997) or by decreasing its carbonate and bicarbonate contents with the addition of acids/acid formers, either to soil or water (Gumaa et al., 1976; Frenkel et al., 1978; Gupta, 1990; Burt, 1998; Griffen and Silvertooth, 1999). Thus neutralization of water RSC with the use of proper amount of gypsum or acid is widely recommended, although use of gypsum is highly economical (Chabbra, 1996; Ghafoor et al., 2001a) but has low solubility of 0.24-0.30 g per 100 ml water at 25 ^{0}C (US Salinity Lab. Staff, 1954, Gupta and Gupta, 1997) and thus from gypsum, a Ca^{+2} concentration of up to 4 me L^- can be obtained in flowing irrigation water (Ayers and Westcot, 1985). On the other hand low dissolution rate of gypsum, however, is an additional advantage to sustain the availability of calcium and electrolyte concentration to maintain the hydraulic conductivity and structure of soils (Reeve and Doering, 1966; Jurinack et al., 1984; Ayers and Westcot, 1985; Rengasamy and Olsson, 1993). The use of commercial mineral acids has been found 5-7 times more expensive than gypsum (Agarwal et al., 1982; Abrol et al., 1988; Ghafoor et al., 2002a) and handling is also difficult and dangerous (Havlin et al., 2002). As alternative, Sulfurous Acid Generator (SAG) is a recently introduced technology to treat saline-sodic/sodic waters. Sulfur

(S) is burnt to produce SO_2 in a chamber, which is made to dissolve in a fraction (1/15th - 1/20th) of tube well water to form sulfurous acid (H_2SO_3) although the solubility of SO_2, in water is limited. This H_2SO_3 neutralizes CO_3^{2-} and HCO_3^- ions of water so the RSC of such treated water is reduced, while theoretically, there would not be any benefit regarding the amelioration of water EC and SAR. However experimental data is lacking about the efficiency of the sulfur burners (Stroehlein and Pennington, 1986), which necessitates the need of field trials before launching the marketing phase of these sulfur burners.

Keeping in view the above facts, an experiment was carried out to study the economics and monitor the effectiveness of SAG treatment of brackish water and other water/soil applied amendments for rice – wheat - rice production on a normal soil using high EC, SAR and RSC tube well water.

2 MATERIALS AND METHODS

A field experiment on 0.75 ha piece of alluvial soil was conducted at Post Graduate Agricultural Research Station (PARS), Univ. Agriculture, Faisalabad-Pakistan, on normal (non-saline and non-sodic), calcareous soil using brackish tube well water (EC = 3.24 dS m^{-1}, SAR = 17.23, RSC = 5.44 $mmol_c$ L^{-1}, pH 7.6) during May 2001 to December 2002. The treatments included;

- T_o Control (all irrigation with untreated tube well water - T/W).
- T_1 All irrigations with SAG treated water 1/15th - 1/20th water passes through SAG, then mixed with remaining flow of T/W water and used for irrigation.
- T_2 Alternate irrigation of SAG treated water and one of tube well water.
- T_3 One irrigation with SAG treated and two irrigations with untreated T/W water.
- T_4 Farm Yard Manure (FYM @ 15 t/ha/yr before transplanting each rice crop)
- T_5 Soil-applied gypsum (agri. Grade passed through 30 mesh sieve having 70% purity) to each crop equal to decrease in RSC as affected by SAG treatment (decrease in RSC equal to that of SAG treated water).
- T_6 H_2SO_4 applied through fertigation equivalent to that affected by SAG treatment (i.e. decrease in RSC equal to that of SAG treated water).

The experiment was laid out in RCBD with three replications following rice-wheat-rice crop rotation. Rice cv. *Basmati 2000* was transplanted in July 2001 followed by wheat *cv. Aqab 2000* during *Rabi 2001* and rice *cv. Basmati 2000* during *Kharif 2002*. A total of 54 treated and 8 untreated irrigations (each of 7.5 cm) were applied to these three crops and there was negligible rainfall during the period of studies. Soil samples were drawn from 00-15 cm and 15-30 cm soil depths at the start of experiment and after the harvest of each crop. The cultural practices, like weeding, fertilizer application as well as amount of irrigation water was kept uniform for all the treatments. The NP fertilizer application rate was 100 and 50 kg ha^{-1} as urea and DAP respectively for both the rice and wheat crops. Soil analysis (pH, EC_e, soluble Na^+, Ca^{++}, Mg^{++}, K^+, $CO_3^{- -}$, Cl^-, SAR, lime contents) was accomplished following the methods described by the US Salinity Lab. Staff (1954). The crops were harvested at biological maturity to record biomass; and were threshed manually to obtain `economic yields. The data were subjected to statistical analysis following the ANOVA technique and 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. The experiment was terminated during December 2002 as the SAG was removed away by the donor agency (*Sweet Water International* and *On Farm water Management Directorate, Punjab-Pakistan*) to some other site.

Table 1 Properties of soil at PARS before the experiment

Soil depth (cm)	Property	R_1	R_2	R_3	Mean
00-15	pH_s	8.40	8.57	8.49	8.49
	EC_e (dSm^{-1})	3.54	2.19	3.60	3.11
	SAR	19.5	10.4	19.0	16.3
15-30	pH_s	8.20	8.61	8.52	8.45
	EC_e (dSm^{-1})	5.41	2.28	3.74	3.81
	SAR	21.2	13.9	23.0	19.4
00-30	Texture	Sandy loam	Loamy sand	Sandy loam	Sandy loam
10-15	B.D (Mg m^{-3})	1.59	1.54	1.67	1.60
20-25	B.D (Mg m^{-3})	1.59	1.54	1.74	1.62
30-35	B.D (Mg m^{-3})	1.58	1.52	1.65	1.58
I.R (cm h^{-1})		1.01	1.26	1.06	1.11

2.1 Tube Well Water and Changes in Quality:

The quality of water was not suitable for irrigation (Table 2) considering the national irrigation water quality criteria of WAPDA, DLR, Hussain (Muhammed and Ghafoor, 1992), India (Gupta and Gupta, 1997; Agarwal et al., 1982; Gupta, 1997) or the other world (Abrol et al., 1988; Ayers and Westcot, 1985). As the continued use of such quality water for irrigation will inevitably increase the price to be paid by the farmers to sustain irrigation farming (Rengasammy and Olsson, 1993) thus a sound management strategy is ever needed to take in to account the predictable long-term adverse effects of sodification and salinization on agriculture and environment (Gritsenko and Gritsenko, 1999). Proper rates and frequency of acids/acid formers can be used to reduce carbonates and bicarbonates in low quality water (Gumaa et al., 1976; Finck, 1982; Whipker et al., 1996; Burt, 1998; Griffen and Silvertooth, 1999; Halvin et al., 2002) and thus could be beneficial by reducing hardness (Christensen and Lyerly, 1954) and crusting in soils, where precipitated $CaCO_3$ acts as a cementing agent (Stroehlein and Pennington, 1986).

Although use of sulfuric acid is most efficient to neutralize the soda and alkalinity in the irrigation water but the concentrations of Na^+ and Ca^{2+} can only be equalized in the course of water treatment if M < 2.0 g/l and $Na^+/Ca^{2+} \leq 0.0$ (Lotovitskii and Bilai, 2001). However experimental data are lacking about the effectiveness of recently introduced sulfur burners, which produce SO_2 to form H_2SO_3 after mixing in water (Stroehlein and Pennington, 1986). Moreover economic considerations are essential whenever there is use of acid forming materials for the improvement of soil and water quality (Fuller and Ray, 1963; Alawi et al., 1980; Ghafoor et al., 2001a) and researchers like Christensen and Lyerly (1954) in a six-year study have found the use of sulfuric acid uneconomical for the treatment of water as well as soil.

Table 2 Sulfurous acid generator treatment of tube well brackish water

Tube well Water Quality Before SAG Treatment			Water Quality During SAG Treatment			Water Quality After SAG Treatment		
EC	**SAR**	**RSC**	**EC**	**SAR**	**RSC**	**EC**	**SAR**	**RSC**
3.32	16.29	5.25	3.38	16.24	0.00	3.37	16.20	4.85
3.51	17.85	5.50	3.74	18.96	0.00	3.56	17.97	2.52
3.38	15.14	4.99	3.65	16.11	0.00	3.42	15.08	1.75
3.27	16.61	5.80	3.30	13.03	0.90	3.34	13.52	3.10
3.04	15.20	5.02	27.5	15.17	0.00	3.13	15.97	4.35
3.30	16.38	5.50	10.4	16.70	0.00	3.31	16.55	4.36
3.41	18.65	5.70	3.42	18.80	0.00	3.58	19.61	3.18
3.58	18.57	7.00	9.68	18.15	0.00	3.65	18.92	3.40
3.41	15.49	6.30	5.05	15.82	0.00	3.71	17.58	3.80
3.11	16.06	6.40	12.1	15.88	0.00	3.18	16.50	3.40
3.11	17.67	5.70	5.85	15.39	0.00	3.10	16.44	3.70
3.06	15.75	7.50	6.24	N/A	0.00	3.09	15.52	4.50
3.02	14.70	5.90	3.16	N/A	0.00	3.02	13.63	4.90
3.15	18.76	4.70	7.43	15.90	0.00	3.35	16.55	2.10
3.23	15.92	5.70	3.32	16.61	0.00	3.29	16.34	4.00
2.99	17.67	5.70	3.45	17.33	0.00	2.98	15.94	4.00
3.11	17.41	5.50	4.38	15.98	0.00	3.06	18.23	4.45
3.09	18.51	5.60	6.14	16.03	0.00	3.08	17.70	4.55
3.19	19.73	3.50	4.14	17.26	0.00	3.25	20.15	4.00
3.16	19.52	4.00	3.83	17.41	0.00	3.29	18.93	2.15
Av.: 3.22	***17.09***	***5.56***	***6.51***	***16.49***	***0.05***	***3.29***	***16.87***	***3.65***
% Variation			**101.9**	**-3.5**	**-99.2**	**2.05**	**-1.33**	**-34.4**

It is clear from the data (an average of 20 irrigations) that SAG treatment of brackish water did not decrease EC_{iw}, rather there was an average increase of 2.1%. (Miyamoto et al., 1975; Stroehlein and Pennington, 1986). Moreover after treatment with SAG water pH comes down from 7.6 to 6.6 (13.2 % decrease, data not shown), which may be attributed to the negligible buffering capacity of the irrigation water. Several researchers in field (Christensen and Lyerly, 1954; Griffen and Silvertooth, 1999), green house (Thorne, 1944), laboratory (Gumaa et al., 1976), and pot (Aldrich and Turrell, 1950) studies have demonstrated desired reduction in pH of the irrigation water with the use of sulfuric acid. SAG did not put any significant decrease in SAR_{iw} (i.e. 1.3% decrease). This nominal decrease in SAR_{iw} may be due to a negligible improvement in the concentration of Ca^{2+} present in irrigation water or this might be due to release of Ca from silt/clay particles suspended in irrigation after acid treatment. In a study Miyamoto et al., 1975b, concluded that after addition of acid in to irrigation water reduces its SAR_{adj}, which shows that Ca^{+2} will tend to remain in solution rather than precipitating out as $CaCO_3$. Our findings are further supported by the research work of Lotovitskii and Bilai (2001), who explored that "Acidification of irrigation water affects not only the concentrations of CO_3^{2-}, and HCO_3^-, but, to a certain extent, the water chemistry as a whole, that is mainly caused by substitution/exchange reactions between salts of the acid and those dissolved in water. In the first minutes after treatment, Na^+, and Cl^- concentrations are unstable and are decreased by 5-15%; however, both almost recover their initial value. The concentration of SO_4^{2-} increases by 10-16% (at the most efficient rate of H_2SO_4 to neutralize alkalinity problem i.e. 40g m^{-3}). The concentration of Ca^{2+} in most cases increases by 8-14%, Mg^{2+} concentration decreases by up to 8%."

Although SAG treatment of brackish water decreased its RSC by about 34.4% (i.e. from 5.56 $mmol_c$ L^{-1} to 3.65 $mmol_c$ L^{-1} but still it was higher when compared to the safe limit of 2.5 $mmol_c$ L^{-1} which is mostly considered the maximum upper limit for safe irrigation in Pakistan (Muhammed and Ghafoor, 1992) and the world (Ayers and Westcot, 1985; US Salinity Lab. Staff, 1954; Gupta and Gupta, 1997). Such level of RSC is generally expected to create some infiltration problems on fine textured soils (Frenkel et al., 1978) or could induce disorders in the nutrient availability as well as plant assimilation (Ayers and Westcot, 1985; Abrol et al., 1988). The results are in line with those of Gale et al. (2001), who in a level basin irrigation study, monitored the efficiency of a sulfur burner, where pH was the only property of the water, significantly affected by the sulfur burner treatment. Summarily there was 7.5% decrease in pH, 0.96% increase in Na, 4.6% increase in Ca+Mg, 8.0% decrease in HCO_3^-, and 4.2% decrease in SAR_{adj}. The low efficiency of the sulfur burner was attributed to its ability of uptake and onward treating of only about 5% of the water flowing through water channel and again diverting that treated portion in to rest of 19 untreated portions. Moreover low efficiency of SAG may also be attributed to low solubility of SO_2 in irrigation water (Miyamoto et al., 1975a; Cotton and Wilkinson, 1967). These results are supported by the research findings of Miyamoto et al., (1975a) who concluded that sulfuric acid not only increases the electrolyte content of the water, but also reduces or removes the carbonate and bicarbonate as well thus the adjusted SAR is decreased, which shows that Ca will tend to remain in solution rather than precipitating out as $CaCO_3$.

As claimed by SAG manufacturing company (*Sweet Water International*), that brackish water treated with SAG may be used to reclaim saline-sodic/sodic soil successfully, the authors are of the view that SO_2 may be too insoluble to accomplish soil reclamation if added to the water (Stroehlein and Pennington, 1986). Therefore low rates of amendments as commonly water-applied should be expected only to affect water quality and the surface soil rather than the entire root zone. Thus high Na soils should generally be treated directly and not by water treatment, with acids/acid formers/Ca providing materials (Stroehlein and Pennington, 1986).

2.2 Soil Properties:

2.2.1 pH_s

The data (Table 3) after three crops show a minor decrease (up to 2.5%) and increase (up to 5.3%) in pH_s at 0-15 and 15-30 cm soil depths. At 0-15 cm depth, there was maximum decrease in pH_s (2.5%) for farmyard manure (FYM) treatment, which could be attributed to the formation of carbonic acid upon the release of CO_2 during its decomposition, while decrease was minimum (0.8%) with T_6 where sulfuric acid (commercial grade) was applied through drip irrigation method. For 15-30 cm depth, all the treatments increased soil pH_s except gypsum treatment, increase being maximum with T_2 (5.3%) and minimum with T_4 (1.4%) and T_0 (2.6%). Gypsum application perhaps maintained a high EC : SAR ratio at both the depths and high EC : SAR ratio tends to lower pH_s and vice versa, in general (Ghafoor et al., 2001b; Ayers and Westcot, 1985; Abrol et al., 1988). A decrease in soil pH_s after addition of gypsum has also been reported by Cates et al., (1982) while reclaiming a calcareous saline-sodic soil. Failure to obtain a marked decrease in soil pH_s may be attributed to buffering effect of the salts present in irrigation water against H^+ addition (Christensen and Lyerly, 1954), and to the presence of $CaCO_3$ in this calcareous soil which acts as a buffer and resists any appreciable change in soil pH_s in the alkaline range (Deverel and Fujii, 1990; Leoppert and Suarez, 1996). Moreover, it is uneconomical and quite impractical (Havlin et al, 2002) to lower the pH_s of calcareous soil because of too much amounts of acids/acidifiers required to serve the purpose (Imas, 2000).

2.2.2 ECe

At the start of the experiment EC_e of soil at 0-15 and 15-30 cm depth on the average was 3.1 and 3.8 dS m^{-1} with non-significant differences among all the treatment plots. After the harvest of final crop relatively greater EC_e especially in surface soil was noted in continuous acid treated plots (T_1 & T_6) against gypsum treated plots that might be due to acid reaction with native lime present in the soil. Mace et al., 1999 in a study have reported greater EC_e values compared to gypsum, presumably from the gypsum supersaturation and elevated alkalinity in the soil system. Similarly after the harvest of final rice crop, a decrease in soil EC_e was more in acid treated plots than control plots. The results are in line with those of Cate et al., (1982) who reported that acid treatment significantly lowered soil EC_e than control plots.

Table 3 Average variation in Soil pH$_s$ during SAG Experiment at PARS before start of Experiment (2001) up to after 2nd Rice Crop –2002 (00-15 cm Depth)

Treatment	Before 1st rice	After 1st rice	After 1st wheat	After 2nd rice	EC : SAR	% var. after 3 crops
T_0	8.47	8.60	8.34 ab	8.37 c	0.38	-1.2
T_1	8.37	8.61	8.30 ab	8.42 bc	0.29	+0.6
T_2	8.50	8.69	8.21 b	8.59 ab	0.18	-1.1
T_3	8.48	8.68	8.30 ab	8.62 a	0.17	+1.7
T_4	8.55	8.57	8.33 ab	8.34 c	0.28	-2.5
T_5	8.56	8.58	8.38 a	8.47 abc	0.19	-1.1
T_6	8.48	8.62	8.26 ab	8.41 bc	0.26	-0.8
SD$_{0.05}$	0.36^{NS}	0.15^{NS}	0.17*	0.19*		

(15 - 30 cm Depth)

Treatment	Before 1st rice	After 1st rice	After 1st wheat	After 2nd rice	EC : SAR	% var. after 3 crops
T_0	8.43	8.64 ab	8.36 ab	8.65 ab	0.15	+2.6
T_1	8.40	8.69 a	8.46 a	8.75 ab	0.14	+4.2
T_2	8.37	8.72 a	8.18 c	8.81 a	0.14	+5.3
T_3	8.40	8.64 ab	8.31 abc	8.74 ab	0.16	+4.1
T_4	8.48	8.68 a	8.31 abc	8.60 b	0.23	+1.4
T_5	8.64	8.63 ab	8.32 abc	8.61 b	0.21	-0.4
T_6	8.39	8.51 b	8.22 bc	8.63 b	0.1	+2.9
LSD$_{0.05}$	0.33^{NS}	0.14*	0.17*	0.17*		

Overall the soil EC$_e$ (Table 4) decreased with all the treatments except with T_4 at 0-15 cm. At both the depths, control plots showed maximum EC$_e$, which may be attributed to no treatment of soil and water. At 0-15 cm depth, maximum decrease was noted with T_3 (45.8%) followed by T_2, T_1, T_6, T_0, and T_5 (1.6%) while increase (37%) was only in FYM treatment plots. This increase in EC$_e$ with FYM might be due to accumulation of salts after mineralization of organic matter as reported by (Hao and Chang, 2003) who explored significant increase in soil salinity levels due to increased levels of soluble Na^+, K^+, Mg^{2+}, Cl^-, HCO_3^-, and SAR, after 5, 10, 15, 20 and 25 years of manure application under both irrigated and non-irrigated conditions. The authors further estimated an annual increase in EC$_e$ (0-150 cm of soil depth average) by 0.1108 dSm^{-1} for every ton of salt applied through the cattle manure under non-irrigated conditions during a long-term study. At 15-30 cm soil depth, decrease in EC$_e$, was maximum with T_3 (66.0%) followed by T_6, T_4, T_2, T_1, T_0 and T_5 (42.0%). The observed values of soil EC$_e$ at both the depths has been maintained below the critical level of 4 dS m^{-1} regarding the productivity of most of the crops and soils (Ayers and Westcot, 1985; US Salinity Lab. Staff, 1954; Gupta and Gupta, 1997) by all the treatments under investigation in this well drained, medium textured, moderately calcareous soil. This could be attributed to high leaching fraction (LF) achieved thus better management of irrigation water (Chang et al., 1982) as two rice and one wheat crop were grown with 62 irrigations (each irrigation of 7.5 cm). However, for fine textured soils with low infiltration rates, to expect similar situation might not be correct for which additional studies are imperative.

Table 4 Average variation in Soil EC$_e$ during SAG Experiment at PARS before start of Experiment (2001) up to after 2nd Rice Crop –2002 (00-15 cm Depth)

Treatment	Before 1st rice	After 1st rice	After 1st wheat	After 2nd rice	% variation after 3 crops
T_0	3.29	2.76 a	5.31 a	3.15 a	-4.3
T_1	3.93	2.27 ab	4.49 a	3.10 a	-21.1

T_2	3.21	1.93 b	4.85 a	1.94 b	-39.6
T_3	3.41	2.16 ab	6.46 a	1.85 b	-45.8
T_4	2.19	2.32 ab	5.42 a	3.00 a	+37.0
T_5	2.47	2.60 ab	4.65 a	2.43 ab	-1.6
T_6	3.28	2.52 ab	6.29 a	2.70 ab	-17.7
$LSD_{0.05}$	2.42^{NS}	0.83*	2.12*	0.91*	

(15 - 30 cm Depth)

Treatment	Before 1st rice	After 1st rice	After 1st wheat	After 2nd rice	% variation after 3 crops
T_0	3.77	1.67	6.27 a	1.84 a	-51.2
T_1	3.62	2.12	4.76 b	1.68 ab	-53.6
T_2	3.63	1.74	5.04 b	1.44 b	-60.3
T_3	4.00	1.63	5.01 b	1.36 b	-66.0
T_4	4.59	1.80	5.38 b	1.80 a	-60.8
T_5	2.93	1.73	4.89 b	1.70 ab	-42.0
T_6	4.12	2.02	6.28 a	1.45 b	-64.8
$LSD_{0.05}$	2.41^{NS}	0.57^{NS}	0.75*	0.35*	

2.2.3 SAR

The SAR of soil at 0-15 and 15-30 cm depth, on the average was 16.3 and 19.4 mmol $L^{-1})^{1/2}$ as four plots each in replication 1 & 3 [under control (T_0), FYM (T_4), sulfuric acid fertigation (T_6), all irrigations with SAG treated water (T_1) treatments] were slightly Na-affected, which on the average tended to keep the soil SAR> 15 -- the critical limit of sodic soils (Ayers and Westcot, 1985, US Salinity Lab. Staff, 1954). The soil SAR (Table 5) fell to about 8 – 12 at both the depths with non-significant differences among all the treatments. At 0-15 cm depth, maximum decrease was noted with T_1 followed by T_0, T_6, T_4, T_2, T_3 and T_5. The relatively better decrease for soil SAR in acid treatment plots i.e. T_1 and T_6 may be attributed to more efficient production of soluble Ca as a consequence of gypsum supersaturation with the acid treatment (Mace et al., 1999). The minimum decrease in soil SAR with gypsum might be due to very low rates of gypsum application and 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. At 15-30 cm soil depth, decrease in soil SAR was found maximum with T_4 followed by T_5, T_3, T_6, T_1, T_2, and T_0. After 3rd crop similar effectiveness (non-significant differences among treatments) of acid and gypsum treatments for reducing soil SAR have also been reported by Cate et al., (1982) which was attributed to very low initial ESP (i.e. 32) of the soil. Our results are also similar with those of Chaudhry et al (1989) who reported that SAR in all plots was significantly decreased with non-significant differences among control, gypsum @ 50% SGR and sulfuric acid @ 50% SGR treatments used for reclamation of moderately salt-affected, loam soil by growing four rice and four wheat crops in rice-wheat rotation. In the current study, observed values of soil SAR at both the depths has been maintained well below the critical level of 15 regarding health of most of the crops and soils (US Salinity Lab. Staff, 1954, Ayers and Westcot, 1985; Gupta and Gupta, 1997) by all the treatments under investigations in this well drained, medium textured, moderately calcareous soil. However, for fine textured soils with low infiltration rates or non-calcareous soils, to expect similar behavior might not be correct for which additional studies for longer periods are imperative. Treatments like those under report are purely aim at to counter the sodicity hazards (SAR and RSC) of irrigation waters for soils and crops productivity. Moreover there is also reported potential danger of soil sodication as a result of the application of high sulfate irrigation water which might be due to the fact that SO_4^- ions in excess to Ca precipitating, may result in Ca-desorption from the colloidal complex to its neutrality in the soil solution (Javid and Ali, 1999).

The present results help to opine that for well drained soils, waters with SAR and RSC higher than conventional levels (Ayers and Westcot, 1985, Abrol et al, 1988, Muhammed and Ghafoor, 1992; Chabbra, 1996) could be successfully used to grow rice and wheat crops, and that the rate of amendments application could be decreased to make the soil-water-crop production system cost-effective. However, to validate and quantify the ideas expressed here, there is need of farm level studies to exploit the poor quality water resources for canal water deficit Pakistan (Ghafoor et al., 2002b) without disturbing the biosphere equilibrium of the crop husbandry and the environment.

Table 5 Average variation in Soil SAR during SAG Experiment at PARS before start of Experiment (2001) up to after 2nd Rice Crop –2002(00-15 cm Depth)

Treatment	Before 1st rice	After 1st rice	After 1st wheat	After 2nd rice	% variation after 3 crops
T_0	16.64 ab	18.82	25.58	8.39	-49.6

T_1	21.07 a	17.88	22.38	10.69	-97.1
T_2	15.21 ab	15.68	23.03	10.87	-28.5
T_3	14.59 ab	17.25	25.07	10.96	-24.9
T_4	16.11 ab	16.43	23.04	10.68	-33.7
T_5	13.49 b	18.04	22.91	12.72	-5.7
T_6	17.09 ab	19.22	24.52	10.36	-39.4
$LSD_{0.05}$	6.56*	5.72^{NS}	3.37^{NS}	5.02^{NS}	

(15 - 30 cm Depth)

Treatment	Before 1st rice	After 1st rice	After 1st wheat	After 2nd rice	% variation after 3 crops
T_0	20.64	13.90	25.17 a	12.13	-41.2
T_1	21.85	14.50	19.66 bc	12.03	-44.9
T_2	18.61	12.61	16.52 c	10.61	-43.0
T_3	17.86	13.09	20.61 b	8.66	-51.5
T_4	18.58	12.39	21.53 ab	7.86	-57.7
T_5	17.04	11.61	19.27 bc	8.03	-52.9
T_6	21.06	14.21	22.91 ab	11.31	-46.3
$LSD_{0.05}$	8.03^{NS}	5.27^{NS}	3.69*	4.68^{NS}	

2.3 Crops Yields

The results of soil analysis reveal that effects of all the treatments on EC_e, SAR and pH_s were comparable in favour of soil and crop health and their productivity, since all the three soil quality parameters were maintained well below the threshold values for rice and wheat crops production (Mass and Hoffman, 1977). Therefore, minor differences have been recorded for grain/paddy yields (Table 6). The results are in line with those of Bauder and Brock (2001) who in a column study on normal, silty clay soil (EC 2.47 dS/m, SAR 5.36 and ESP 6.9%) explored that the use of poor quality waters (EC 0.97 & 2.21, SAR_{adj} 2.5 & 16.6 and RSC 0 & 0) did not significantly affect the yields of alfalfa, sordan grass and barley. For better and clear differences among treatments, the study should have been continued for a period of another 2-3 years. The yield trends for all the three crops grown seem 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* and reported markedly higher pasture yields for sulfuric acid treatment plots than those of the plots treated with gypsum during initial years. However, 20 months after the application of treatments, there was no significant difference among yields of H_2SO_4 and gypsum treatment plots.

Table 6 Effect of treatments on straw and paddy/grain yields (kg ha^{-1}) of rice and wheat crops

Treatments	**Rice 2001**		**Wheat 2001-02**		**Rice 2002**	
	Straw	**Paddy**	**Straw**	**Grain**	**Straw**	**Paddy**
T_0	2845	1357 c	4486	2570 b	5491	3106
T_1	4647	2354 ab	5175	3368 a	3840	2797
T_2	3913	2048 b	5001	3518 a	4333	2884
T_3	4723	2434 ab	4949	3434 a	4208	2846
T_4	5136	2660 a	5231	3430 a	5038	3203
T_5	4115	2237 ab	5060	3630 a	4275	2726
T_6	4708	2339 ab	5218	3517 a	4405	2803
$LSD_{0.05}$		532.1^*		282.6^*		1076^{NS}

For 1st rice crop yield, maximum crop yield was obtained with sulfuric acid fertigation treatment of brackish water compared to gypsum treatment, although with non-significant difference. Similar results were obtained by Chaudhry et al., 1989 for 1st rice crop grown during kharif 1982. An increase in yield over control plots, with the addition of sulfuric acid have 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 significantly higher paddy yields with acid treatment, closely followed by gypsum while minimum paddy and straw yield was obtained from the control plots. Moreover 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 nutrient availability (Ryan et al., 1975a, Ryan et al., 1975b; Ryan and Stroehlein, 1979). In a field study by Chapman an increase in rice grain yield of 16% with sulfuric acid treatment plots over gypsum treatments plots have been reported that was attributed to increased nutrient availability due to addition of sulfuric acid after its instantaneous reaction with the soil (Havlin et al., 2002).

For wheat crop, the acid and gypsum treatments had statistically similar yields but significantly higher than control. Results like these have been reported by Akram et al (1989) who explored similar yields of wheat for gypsum and acid treatments, which were significantly higher than control while comparing reclamation efficiency of gypsum and acid treatments in a laboratory study using a highly saline-sodic soil. For 2nd rice crop all the treatments showed non-significant differences for paddy yield.

2.4 Economics Analysis

Economic considerations are essential whenever there is use of acid forming materials for the improvement of soil and water quality (Fuller and Ray, 1963; Alawi et al., 1980). Several researchers in Pakistan (Ghafoor and Muhammed 1981; Ghafoor et al. 1986; Bhatti, 1986; Chaudhry et al, 1989; Ghafoor et al, 1997; Ghafoor et al., 1998; Ghafoor et al, 2001a), India (Yadav (1973), and else of the world (Christensen and Lyerly, 1954; Havlin et al., 2002) have already reported sulfuric acid application to soil as uneconomical and several times expensive than gypsum. On the other side, economic analysis have never been reported in several studies about the use of H_2SO_4 on calcareous soils (Throne, 1944; Overstreet et al., 1951; Overstreet et al., 1955; Mathers, 1970; Ryan et al., 1975a; Ryan et al., 1975b; Prather et al., 1978; Ryan and Stroehlein, 1979; Ashraf, 1979; Nadeem, 1981; Mian and Baig, 1982; Mace et al., 1999; Peterson, 2000).

For the present study economic analysis was done by using the partial budgeting appraisal. Gross benefit, variable cost and net benefit was computed for each treatment for the rice-wheat-rice rotation. The data (Table 7) show that both the gross benefit and variable costs remained relatively more for rice than those from wheat cultivation. On the basis of three crops, maximum total variable cost was incurred on T_1 followed by T_6, T_2, T_3, T_5 and T_4 while no variable cost on the control treatment. Total gross benefit realized was highest for the treatment T_4 followed by T_5, T_3, T_0, T_2, T_6, and T_1. Thus the economic analysis favours the use of organic matter and gypsum to counter the sodicity hazards of irrigation waters and for sustainable yield of rice and wheat crops. The use of sulfur burner/ sulfuric acid was found to be around 5 times costlier than gypsum in our study. Similar results have been reported by Chaudhry et al., 1989 where on economic grounds, gypsum application @ 100% GR was found most economical although maximum paddy and wheat grain yields, through out the experiment, were obtained with H_2SO_4 applied equivalent to 50% SGR. Similarly Christensen and Lyerly (1954) in a six-year study have also found the use of sulfuric acid uneconomical for the treatment of water as well as soil.

Table 7 Economic analysis (US$ ha^{-1}) of SAG and other treatments of brackish water for rice and wheat crops

Treat ment	Gross benefit			Total Gross Benefit	Variable cost			Total Variable Cost	Net Benefit
	Rice	Wheat	Rice		Rice	Wheat	Rice		
T_0	261	396	582	1239	--	--	--	--	1239
T_1	444	507	525	1476	326	38	288	652	825
T_2	388	523	541	1452	163	22	146	331	1120
T_3	459	512	534	1504	109	13	97	219	1286
T_4	500	516	600	1616	31	--	31	63	1553
T_5	422	538	512	1473	58	7	56	121	1352
T_6	441	527	526	1494	305	35	293	633	861

Note: Costs of inputs were calculated as per market rates and of produce as support prices

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