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Gypsum: An Economical Amendment for Amelioration of Saline-Sodic Waters and Soils, and for Improving Crop Yields

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ABSTRACT

The Indus Plains of Pakistan are situated in arid to semi-arid climate where monsoon rains are erratic and mostly fall in the months of July, August and March, which are quite insufficient to grow even a single crop without artificial irrigation. To make the agriculture a success under the ambient agro-environment, a net work of gravity flow surface irrigation canals is handling 111.1 MAF water, about 48 MAF pumped ground water from > 0.4 million tube wells and sewage irrigation around urban dwellings. At present, 6.3 mha soils are salt-affected and 70-80% of the pumped ground water is hazardous for irrigation. Competition among the agricultural and non-agricultural uses has decreased the sweet water availability for the former sector, which is expected to continue in future. As a consequence, brackish ground water (high EC, SAR, RSC) is being pumped more and more to practice irrigated agriculture that might be a sustainability risk in the long run. Water quality parameters include EC for total soluble salts, and SAR (high sodium with low Ca^{2+}+Mg^{2+}) and RSC (high CO_3^{2-}+HCO_3^- or low Ca^{2+}+Mg^{2+}) reflect the sodicity hazards. The ground water, drainage water and sewage become hazardous because of high EC (>1.0 dS m^{-1}), SAR (>10.0) and/or RSC (>2.5 $mmol_c$ L^{-1}). For lowering high EC of water, only dilution with low electrolyte water is the option. In this case, use of any amendment (gypsum, acids, acid formers) will increase it further without any beneficial effect. To lower high water SAR, gypsum is the most economical amendment, dilution will decrease it by the square root times of the dilution factor, while use of any acid (sulphurous acid or sulphuric acid) or acid former has to do nothing with high water SAR rather will induce cost-intensiveness without any gain rather may deteriorate the soil health (physically and chemically) if acids or acid formers are used for longer periods. For high RSC, dilution with low CO_3^{2-}+HCO_3^- water will decrease it proportionately to the dilution factor, Ca-salts will increase Ca^{2+}+Mg^{2+} to affect a decrease in water RSC, while acids or acid formers will neutralize CO_3^{2-}+HCO_3^- to decrease water RSC. Among RSC treatment amendments, the use of gypsum is economical and safe, while acids could accomplish the same but at a much higher cost. For reclaiming saline soils ($EC_e \geq 4.0$ dS m^{-1}, SAR ≥ 13.0), no amendment is required rather simple leaching with all the types of water (canal, ground water, agricultural drainage) is useful during early phase of reclamation following a gradual shift toward sweet water application. For saline-sodic ($EC_e \geq 4.0$ dS m^{-1}, SAR ≥ 13.0) and sodic soils ($EC_e \geq 4.0$ dS m^{-1}, SAR ≥ 13.0), Ca-carriers (gypsum, calcium chloride, calcium nitrate, phospho-gypsum, later three being industrial by-products) are economical, acids (H_2SO_4, HCl, HNO_3) or acid formers (sulphur, calcium poly-sulphide, pyrite, ferrous sulphate) can reclaim such soils relatively at a faster rate but at 5-10 times higher cost.

Key Words: Gypsum; Saline-sodic waters and soils; Acids; Rice; Wheat

1. RATIONALE

Irrigated agriculture consumes major share of good quality waters, which is decreasing because of competing non-agricultural demands and droughts around the world (Gupta, 1990; Sandhu, 1993; Bouwer, 1994). Consequently, relatively poor quality ground water resource in Pakistan is being exploited (Anonymous, 1995). Because of similar reasons, extensive areas (5.7 to 6.3 mha) has been salinated/sodicated up-till-now. It is considered opinion that water is the life-blood to human being, whereas the 21st century brings its own challenges and new dimensions particularly in terms of increased demand for agriculture and domestic water, social and environmental issues as well as technological developments. This necessitates that all the past programmes related to water resources and reclamation of salt-affected soils must be critically examined to learn lessons which can help shape our future for the most optimum and sustainable development, and constructive utilization of the available soil and water resources. One aspect of this scenario pertains to the use of brackish water (high EC, SAR and/or RSC) with or without the application of chemical and organic amendments, and cultural practices. This paper high-lights the economical feasibility of using acids, acid formers and gypsum like amendments for brackish water treatment. Moreover, the impact of treated water application on normal and for reclaiming salt-affected soils under the ambient agro-climatic and socio-economic conditions of Pakistan are reviewed.

2. AGRICULTURAL RESOURCES OF PAKISTAN

2.1. Water resources. The surface water resources are provided by the river Indus and its tributaries (Sutluj, Ravi, Chenab, Jhelum) with average annual farm-gate supplies of 81.95 MAF (Anonymous, 2000; Table I). A fear prevails that these supplies might become short because of silting of Tarbela, Mangla and Rawal water reservoirs along with droughts perhaps as a result of global environmental changes and increasing consumption of fresh water by the non-agriculture sector. In the past, unscientific management of surface water has led to waterlogging and soil salination/sodication in many parts of the country (Ahmad *et al.*, 1998).

Table I. Farm-gate availability of irrigation water (MAF) in Pakistan

Year	Canal water		Ground pumped	Total at
	Canal Head	Farm gate	(Farm gate)	farm gate

1981-82	101.85	62.44	34.47	96.91
1991-92	109.70	77.15	44.90	122.05
1997-98	NA	81.95	40.20	122.15

(Anonymous, 2000)

Hydro-geological conditions of Pakistan are mostly favourable for pumping ground water, quality of which is variable (Table II), i.e. 79% of area in Punjab and 28% of area in Sindh has ground water suitable for irrigation (Mohtadullah, 1997). To combat waterlogging and to meet deficit of canal water supplies, > 0.4 million tubewells are pumping about 48 MAF water annually, of which 40-43 MAF water is used for agricultural purposes (Mohtadullah, 1997; Anonymous, 1998, 2000). Approximately 70-80% of the pumped groundwater in Punjab is classified as hazardous (Malik *et al.*, 1984). It has been computed that 40% is the share of groundwater in total irrigation requirement of crops in Punjab. Some details of ground water quality in Pakistan are given in Table III with respect to Ca : Mg ratio in relation to EC and SAR.

Table II. Quality of ground water in Punjab, Pakistan

Status	Total samples analysed	Per cent
Fit	18605	45
Unfit	22529	55
Total	41134	100

(Soil Fertility Directorate of Punjab quoted by Kahloon *et al.*, 2000)

2.2. Soil resources. Climate of Pakistan is tropical in plains and subtropical in the mountainous regions. Temperature ranges from mean minimum of 4°C during December/January to mean monthly maximum of 38°C during June/July (Kureshi, 1979). The monsoon rains are uncertain and erratic both during summer and winter months. Rate of evapo-transpiration ranges between 150 to 2000 cm annually in different parts of the country (Mohtadullah, 1997). Total area of Pakistan is 813900 sq km. Out of canal commanded area (CCA) of 16.2 mha, 32.53% is very good agricultural land, VGAL (Class I), 42.9% is good agriculture land, GAL (Class II), and 32.5% is marginal agricultural land, MAL (Class III, Table IV). About 2.8 mha of the CCA are culturable waste because of salinity/sodicity and 2.5 mha out of the CCA are saline-sodic in nature (Table Va). Different types of salt-affected soils have been presented in Table Vb (Muhammed, 1983; Mian & Mirza, 1993). About 70% of the salt-affected soils are economically reclaimable if sufficient irrigation water is available and drainage, where needed, is provided (Shams-ul-Mulk & Mohtadullah, 1991; Mian & Mirza, 1993; Mirza & Ahmad, 1998).

Table III. Ground water quality in Pakistan with respect to Ca:Mg, EC and SAR

Punjab				Sindh		
Total soluble salts		SAR	Ca:Mg	Total soluble salts ($mmol_c$ L^{-1})	SAR	Ca:Mg
mg L^{-1}	$mmol_c$ L^{-1}					
400	6.25	3.0	1.00	6.4	2.5	0.56
750	11.70	5.9	0.80	12.0	5.26	0.53
1000	15.60	8.5	0.58	16.0	6.53	0.55
2000	31.25	16.8	0.42	32.0	9.27	0.54
4000	62.50	17.8	0.33	64.0	14.29	0.53

(Computed from Ahmad & Chaudhry, 1988)

Table IV. Land capability classes (mha)

Class	Punjab	Sindh	NWFP	Baluchistan	Pakistan
Total area	20.62	14.10	10.17	34.72	86.91
Area surveyed	20.62	9.22	9.14	19.14	61.81
Class I VGAL	3.49	1.10	0.19	0.46	5.24
Class II GAL	3.68	2.32	0.52	0.44	6.95
Class III MAL	2.40	1.50	0.66	0.20	4.78
Class IV PAL†	1.44	0.22	0.58	0.70	2.99
ClassV GFL‡	-	-	0.17	-	0.17
Class VI–VIII	9.03	3.72	6.40	17.23	36.38

†PAL = Poor agricultural land, ‡GFL = Good forest land(Mian & Mirza, 1993)

Table V. Salt-affected soils of Pakistan (mha)

(a) Under irrigated and non-irrigated conditions

Soil Type	Punjab	Sindh	NWFP	Baluchistan	Pakistan
Irrigated	1.51	1.15	0.93	0.11	2.80
Non-Irrigated	1.16	0.96	0.02	0.39	2.53
Total	2.67	2.11	0.05	0.50	5.33

(Mian & Mirza, 1993)

(b) Types of salt-affected soils of Pakistan (000 ha)

Province	Saline	Saline-sodic		Sodic	Total
		Permeable	Impermeable		
Punjab	504.4	1225.3	856.5	-	2586.2
Sindh	1342.3	673.1	277.6	28.2	2321.2
NWFP	501.6	5.2	9.2	-	516.0
Baluchistan	175.0	125.0	4.4	-	304.4
Pakistan	2523.3	2028.6	1147.7	28.2	5727.8

(Muhammed, 1983)

3. CHARACTERIZATION OF IRRIGATION WATERS

The suitability of water for agriculture is mainly determined by the total and kind of soluble salts, soil and crop types, climate, and skill and knowledge of farmers (Suarez & Lebron, 1993; Van-Schilfgaarde, 1994; Shelhevet, 1994). Important water quality parameters are described here.

3.1. Electrical conductivity (EC). It is a measure of the total amount of soluble salts. Different classification schemes are followed in various parts of the world, which have been reviewed by Muhammed and Ghafoor (1992). Upper permissible EC_{iw} is up to 1.0 dS m^{-1} (US Salinity Lab. Staff, 1954; Ayers & Westcott, 1985). In Pakistan, Water and Power

Development Authority (WAPDA) has proposed permissible EC_{iw} up to 3.0 dS m^{-1} while Department of Agriculture, Punjab considers safe level of total soluble salts up to 1000 ppm, but both the later limits have not been investigated comprehensively at farm level. Anyhow, salts in soils or waters could reduce water availability to crops to such an extent that crop yields are adversely affected (Ayers & Westcott, 1985; Suarez & Lebron, 1993; van Schilfgaarde, 1994; Shelhevet, 1994; Oster, 1994).

3.2. Sodium adsorption ratio (SAR). It is a measure of sodicity hazard of irrigation water due to high Na^+ or low Ca^{2+}+Mg^{2+} concentration. Its permissible limit is less than 10 (US Salinity Lab. Staff, 1954), 8.0 (Ayers & Westcott, 1985), and 18.0 (WAPDA). High SAR induces soil dispersion and structure deterioration leading to infiltration problems, specific ion toxicity, could induce nutrient deficiency or toxicity, and ultimately could reduce crop yields or even crop failure.

3.3. Residual sodium carbonate (RSC). The RSC is also a measure of sodicity hazard of irrigation waters due to high CO_3^{2-}+HCO_3^- or low Ca^{2+}+Mg^{2+}. Its permissible limit is 1.25 $mmol_c$ L^{-1} (US Salinity Lab. Staff, 1954) while WAPDA considers its acceptable level up to 5.0 $mmol_c$ L^{-1}. High RSC could cause Ca^{2+} and Mg^{2+} deficiency, infiltration problems and increase soil solution SAR through promoting precipitation of $CaCO_3$ in soils.

3.4. Infiltration problem. This parameter reflects the soil infiltration problems associated with irrigation waters. Doneen (1975) incorporated all the ions associated with this problem into a formula to estimate the infiltration which was designated as Permeability Index (PI).

$PI = [100 \{Na^+ + (HCO_3^-)^{1/2}\}/\{Na^+ + Ca^{2+} + Mg^{2+}\}]$,-- (1), *conc. in water in* $mmol_c\ L^{-1}$.

It is a useful parameter which does not need any determination in addition to routine water analysis.

3.5. Calcium to magnesium ratio (Ca^{2+}:Mg^{2+}). For most of the situations, Ca^{2+}:Mg^{2+} = 1 : 1 in soil solution or irrigation water is considered safe, while Mg^{2+} proportion higher than this level is thought to promote infiltration problems (Paliwal & Gandhi, 1975; Simson *et al.*, 1979; Rahman & Rowel, 1979; Ayers & Westcott, 1985; Chaudhry *et al.,* 1986; Suarez & Lebron, 1993; Ghafoor *et al.*, 1997a). One concern, however, is that crop productivity is generally low on high Mg^{2+} soils (Agarwal *et al.*, 1982; Gupta & Gupta, 1997) or on soils being irrigated with high Mg^{2+} waters even though infiltration problems might not be evident. Low yields are expected earlier with high Mg^{2+} waters particularly if a source of readily available Ca^{2+} (like $CaCO_3$, $CaSO_4$, $CaMg(CO_3)_2$, is not present in soils.

3.6. EC_{iw}:SAR_{iw} ratio. Low EC_{iw} and/or EC_e tends to decrease soil infiltration through increasing the zeta potential while high SAR_{iw} produces opposite results (Ayers & Westcott, 1985; Girdhar, 1986; Ghafoor *et al.*, 1991, 2000, 2001b; Raza *et al.*, 2000). This quality parameter is very important for brackish water management through maintaining a leaching fraction as well as if used for reclaiming salt-affected soils. However, presently this parameter is not generally considered for water use guidelines but with the increased use of relatively low quality irrigation waters needs even more emphasis.

3.7. Miscellaneous problems. Such problems include high pH_{iw}, N_{iw} concentration, Fe_{iw} and water induced corrosion or soil encrustation. Disease vector problems and heavy metal toxicities often result as a secondary trouble related to a low water infiltration rate, to the use of waste water for irrigation or to poor drainage. Municipal sewage contains metals like Pb, Cr, Ni, Cu, Zn, Fe, Mn, Co, Cd, Se etc. (Alloway, 1990; Hussain *et al.*, 1996; Ghafoor *et al.*, 1994a, 1995, 1996, 2001a; Qadir *et al.*, 1999, 2000a). The heavy metal problems appear to be site-specific but more important and risky since metal excretion is very slow when these enter into human body through food chain.

4. TREATMENT/MANAGEMENT OPTIONS

Adverse impacts, their magnitude and mechanisms of higher values of water quality parameters (Section 3) are different rather site-specific and multifarious. Type and total amount of chemicals in water, physico-chemical soil characteristics, crop type and growth stage, climate, water treatment type, cultural practices, genetic architecture of plants, skill of the farmers and socio-economic conditions and traditions of an area alter the effects of waters and management strategies.

4.1. Use of inorganic amendments

4.1.1. Electrical conductivity (EC). The only available option is dilution with low salt water. Addition of any chemical like gypsum, acid or acid former has to aggravate the problem and will be mere an economical loss rather is spend thrift or luxury. However, high EC_{iw} has proved generally better during the early phase of reclaiming saline-sodic soils because of positive effect of electrolytes on soil infiltration (Shainberg & Letey, 1984; Ghafoor *et al.*, 1985a & b, 1990a; Girdhar, 1986; Gupta, 1990; Murtaza *et al.*, 1996; Oster & Jayawardane, 1999). However, addition of organic matter as farm yard manure and/or green manure could facilitate the hydraulic conductivity which can prolong the appearance of adverse effects of high EC_{iw} on soils and crops (Ghafoor *et al.*, 1997a).

4.1.2. Sodium adsorption ratio (SAR). Water or soil SAR is calculated from total concentration of ions ($mmol_c$ L^{-1}) in water or soil solution by the formula (US Salinity Lab. Staff, 1954):

SAR = Na / (Ca+Mg/2)$^{1/2}$ *--------- (2), ion concentration in mmol*$_c$ *L*$^{-1}$.

The treatment options include:

a. Dilution. Since SAR_{iw} will decrease by square root times of dilution factor or will increase by square root times of concentration factor, dilution of high EC water will also decrease the SAR_{iw}.

b. Use of Ca-amendments. One can think to decrease the Na^+, which is not economical for irrigation water except dilution with low Na^+ water. Other possibility is to increase $Ca^{2+}+Mg^{2+}$ concentration through lining of water courses with gypsum stones (Table VI). This strategy or practice is safe and economical although some problems of rodents, cleaning of water courses or decreasing gypsum stone dissolution through the coating of lime ($CaCO_3$) on the gypsum stone surfaces if water has high RSC_{iw} could be encountered. However, addition of acid or acid formers has to do nothing to decrease water SAR_{iw} as claimed by some researchers (Kahloon *et al.*, 2000) but may affect reclamation of marginal saline-sodic soils if economics is overlooked (Mace *et al.*, 1999; Kahloon *et al.*, 2000). Gypsum stone lining successfully reclaimed saline-sodic soils and improved crop yields at much low costs (Kemper *et al.*, 1975; Ahmad *et al.*, 1976; Ghafoor, 1987; Malik *et al.*, 1992; Oster, 1994). Some comparisons of soil improvement with amendments and their economic evaluation are shown in Tables VII and VIII, respectively from which it is clear that gypsum is the most cost-effective ameliorant for saline-sodic soils and waters.

Table VI. Water quality improvement through gypsum stone lining in water courses

Un-amended water			Amended water			Source
EC	SAR	RSC	EC	SAR	RSC	
3.6	21.0	11.5	4.0	15.8	6.0	Qureshi *et al.* (1975)
3.5	19.5	12.9	3.9	12.0	6.5	Qureshi *et al.* (1977)
1.2	14.4	5.0	1.6	6.8	00	Chaudhry *et al.* (1984)
1.8	9.8	7.1	2.1	8.7	4.6	Ghafoor *et al.* (1987)

EC as dS/m, SAR as $(mmol/L)^{1/2}$ and RSC as $mmol_c/L$.

Table VII. Amended water affects changes in soil (0-30 cm) with and without soil-applied gypsum

Treatment	Soil properties			
	pH_s	EC_e	SAR	ESP
Original soil (1981): Control	8.8	12.1	114.5	71.4
Orig. soil (1981) for soil-applied Gyp @ 75 % SGR*	8.7	20.1	143.9	72.5
Control treatment soil in 1983	8.0	5.2	35.3	36.4
Soil-applied Gyp @ 75 % SGR in 1983	7.8	5.6	18.3	15.4

*SGR = Soil gypsum requirement (Ghafoor *et al.*, 1987)

4.1.3. Residual sodium carbonate (RSC). The RSC calculations assume quantitative precipitation of CO_3^{2-}, HCO_3^-, Ca^{2+} and Mg^{2+} ions upon entry into soils (Eaton, 1950) which is not always true. Upon irrigation, the above mentioned precipitates get dissolved due to dilution while with concentration of soil solution mainly through evapo-transpiration, these compounds could re-precipitate. The precipitation quantity and rate is limited by the lowest amount of any one of these ions. The formula for RSC calculation is:

RSC = $(CO_3^{2-} + HCO_3^-) - (Ca^{2+} + Mg^{2+})$ *---(3), ion conc. in mmol*$_c$ *L*$^{-1}$.

The treatment options include:

a. Dilution. Mixing with low $CO_3^{2-}+HCO_3^-$ or high $Ca^{2+}+Mg^{2+}$ water could decrease the RSC proportionately just like as could be accomplished in case of EC_{iw}.

b. Neutralize $CO_3^{2-} + HCO_3^-$. This is accomplished with mineral acids or acid former (H_2SO_4, HCl, HNO_3 and S etc). Principle chemical reactions of CO_3 with acids (e.g. Na_2CO_3 and H_2SO_4) are:

$2\ Na_2CO_3 + H_2SO_4 = 2NaHCO_3 + Na_2SO_4$ ----- (4)

$2NaHCO_3 + H_2SO_4 = Na_2SO_4 + 2H_2O + 2CO_2$ -- (5)

These reactions will lower pH of water (without changing

Table VIII. Economic of applying gypsum and acids for soil and water amelioration
(a) Drainage water affects soil (0-30 cm) & income (Rs/ha) after 3 years (3 rices+3 wheats)

Treatment	pH_s	EC_e (dS/m)	SAR	Net income
Original soil (Hafizabad series)	7.1 - 7.7	3.2 - 4.9	10.8 - 15.7	-
S1B9 sump water alone, FDPA	8.4	5.0	21.2	73278
Soil-applied gypsum @ water RSC	8.3	5.6	16.1	64750
Water-applied H_2SO_4 @ water RSC	8.4	4.3	19.5	18228
FYM @ 25 Mg/ha/annum	8.4	4.8	21.2	74216

b. Drainage water affects saline-sodic soil (0-30 cm) & income (Rs/ha) after 3 rices+3 wheats

Treatment	pH_s	EC_e (dS/m)	SAR	Net income
Original soil (Khurrianwala series)	7.9-8.4	8.5-32.3	21.0-77.5	-
S1B9 sump water alone, FDPA	8.4	9.8	22.9	28427
Soil-applied gypsum @ 50% SGR	8.4	8.4	21.8	28380
Water-applied H_2SO_4 @50% @ WRSC	8.4	10.3	23.9	- 11719
Soil-applied gypsum @ 100% SGR	8.3	8.5	20.9	35714
FYM @ 25 Mg/ha/annum	8.4	10.1	16.4	35713

For Table VIIIa & b: EC_{iw}=2.93-3.21 dS/m, SAR_{iw}= 12.0-18.2, RSC_{iw}=3.7-10.0 $mmol_c/L$. (Ghafoor *et al.*, 1997b) its SAR) as well as that of the soil receiving this water for longer periods (Tables IX & X). What will happen with the soil if this water treatment is continued for longer periods, has not been properly investigated. However, this practice has not proved economical (Ghafoor *et al.*, 1997a & b, 1998; Qadir *et al.*, 1998), while in other studies economics has not been evaluated even in field studies (Kemper *et al.*, 1975; Ahmad *et al.*, 1976; Manukyan, 1976; Kahloon *et al.*, 2000).

Table IX. Sulphurous acid affects improvement of saline-sodic waters (Av. of 2-year study)

Treatment	pH	EC, dS/m	SAR	RSC $mmol_c/L$
Un-treated Tubewell water	8.5	1.9	13.2	2.7
Sulphurous acid generator treated water	2.8-4.0	2.3	12.1	Nil

(Kahloon *et al.*, 2000)

Table X. Sulphurous acid water treatment ameliorates saline-sodic soil (0-30 cm depth, 2-year study)

Water treatment with rice-wheat crop rotation	pH_s	EC_e, dS/m	SAR
Original soil	8.0	8.1-8.7	21.3-27.6
Soil receiving continuously un-treated tubewell water	8.8	7.0	18.8
Soil receiving alternately un-treated/treated tubewell water	7.5	2.9	11.4
Soil receiving sulphurous acid generator treated water	7.1	1.7	8.1

(Kahloon *et al.*, 2000)

c. Addition of Ca^{2+} + Mg^{2+}. This can be achieved by addition of any calcium salt like gypsum, $CaCl_2$, $Ca(NO_3)_2$ etc., gypsum being the cheapest and the most popular amendment in Pakistan and elsewhere in the world. Powdered gypsum could be incorporated into plough layer of both the normal to counter the adverse effects of high SAR_{iw}/RSC_{iw} and the saline-sodic soils for their reclamation (Malik *et al.*, 1992; Ghafoor *et al.*, 1986, 1987, 1991, 1997b, 1998; Qadir *et al.*, 1998). Even gypsum stone lining in water courses can be done but suitable mainly for water improvement (Kemper *et al.*, 1975; Qureshi *et al.*, 1975, 1977; Chaudhry *et al.*, 1984; Ghafoor *et al.*, 1987). Water course lining option is the cheapest one (Table XI). This practice can successfully reclaim saline-sodic soils with or without soil-applied gypsum (Table XII & XIII).

Table XIII. Gypsum stone lining in water course improves saline-sodic soil at Mona Reclamation Experiment Project

Treatment	pH_s	EC_e, dS/m	SAR
Original soil (0-30 cm)	8.2	0.83	1.83
Soil after 8 crops without water treatment	8.3	0.96	3.69
Gyp. stone lined water course after 8 crops	8.2	0.68	1.94
Soil receiving gyp. @ WGR after 8 crops with untreated water	8.3	0.17	1.11

Untreated pH_{iw}=7.92, EC_{iw}=1.6 dS/m, SAR_{iw}=14.4, RSC_{iw}=5.0 $mmol_c$ /L(Chaudhry *et al.*, 1984).

4.1.4. High Mg^{2+} contents. Comprehensive research has not been conducted to assess the adverse effects of high Mg_{iw}. In some studies, it has been observed that high Mg^{2+} water is equally effective to reclaim saline-sodic soils (Paliwal & Gandhi, 1975; Ahmad *et al.*, 1976; Girdhar & Yadav, 1982; Chaudhry *et al.*, 1986; Ghafoor *et al.*, 1990b, 1992a & b). From various studies, it was also observed that high Mg^{2+} water was relatively more harmful to rice yield (Table XIV) compared to that of wheat/cotton crops (Ghafoor *et al.*, 1997a). This aspect needs further research.

4.1.5. EC:SAR ratio. Low SAR with high EC_{iw} is found better for normal and salt-affected soils because of favourable effect on soil infiltration and HC, while reverse is true for high SAR_{iw} with low EC_{iw}. Invariably during initial phase of reclaiming saline-sodic or sodic soils, most of the EC:SAR ratio waters (1:4 to 8:1) have been found equally useful (Ghafoor *et al.*, 2000, 2001b; Raza *et al.*, 2000) but has to switch to better quality water (low EC_{iw}, low SAR_{iw}) with the advancement of soil reclamation (Verma *et al.*, 1987; Khandewal & Lal, 1991). Results of some studies are shown in Tables XV & XVI regarding the effect EC:SAR ratios of irrigation water or soil solution upon amelioration of saline-sodic soils.

Table XI. Benefit to cost ratio on the basis of 4-year study in Punjab (4 wheat + 3 rice crops)

Treatment	Income (Rs./ha)	Cost (Rs./ha)	Benefit : Cost
Tube well water (EC=1.25 dS/m, SAR=14.4, RSC=5.0 $mmol_c\ L^{-1}$)	20985	11204	1.87
Tube well water passed through gypsum stone lined water course	22461	11544	1.95
Soil-applied gypsum @ water GR	25301	13571	1.86

(Malik *et al.*, 1992)

Table XII. Gypsum stone water course lining improves saline-sodic soil and economics (Rs./ha)at Shahkot

Treatment	pH_s	EC_e, dS/m	SAR	Net profit
Original soil	8.3-8.7	12.9-18.1	122.5-141.2	-
Water passed through gyp. stone lined water course (after 3 crops)	8.3	7.1	50.3	8725/-
Water passed through gyp. stone lined water course + soil applied gyp. @ 75 % soil GR (after 3 crops)	8.0	6.4	21.8	13089/-

Untreated EC_{iw}=1.7 dS/m, SAR_{iw}=10.0, RSC_{iw}=7.45 $mmol_c$/L, SAR_{adj}=23.9 (Ghafoor *et al.*, 1987).

Table XIV. Ratio of Ca:Mg in irrigation waters affects rice and wheat yields on saline-sodic soils

Amendment	Ca_{iw}:Mg_{iw}	Wheat*	Rice*	Source
Nil	1 : 1	50.0	- 17.6	Ghafoor, *et al.*, 1991.
Nil	1 : 6	00	- 65.0	---------- do -------
Lime @ 12%	1 : 6	50.0	- 38.1	Ahmad *et al.*, 1997.
H_2SO_4 @ 100% SGR	1 : 6	111.8	- 11.0	---------- do --------
Phospho-gypsum @ 100% SGR	1 : 6	167.8	- 23.9	Ghafoor *et al.*, 1992b.
FYM @ 25 Mg/ha	1 : 6	55.6	- 68.9	--------- do -------

* Rice and wheat yields are as % over the respective control.

Table XV. Amelioration of loamy clay soils using different EC:SAR ratio waters without gypsum

Treatment	pH_s	EC_e, dS/m	SAR	K_{sat} (cm/h)
Original Soil	8.5	11.2	21.8	-
Canal water	8.2	2.5	12.8	0.48
EC_{iw}:SAR_{iw} :: 6:1.5	7.5	6.3	5.2	0.89
EC_{iw}:SAR_{iw} :: 6:12 .0	7.9	6.5	12.3	0.39
EC_{iw}:SAR_{iw} :: 6:24 .0	8.3	6.3	24.8	0.30
EC_{iw}:SAR_{iw} :: 12:48.0	8.0	14.3	46.6	0.20

(Ghafoor *et al.*, 2001b)

Table XVI. Properties of loam soil as affected by EC_e:SAR_{ss} receiving gypsum @ 50 % soil GR

Treatment	Gyp. mesh size	pH_s	EC_e, dS/m	SAR
EC_e:SAR_{ss} :: 8:8	Passed through 5 mesh	7.76	1.25	1.12
EC_e:SAR_{ss} :: 8:8	Passed through 16 mesh	7.56	1.21	1.18
EC_e:SAR_{ss} :: 8:8	Passed through 30 mesh	7.75	1.37	1.50
EC_e:SAR_{ss} :: 8:48	Passed through 5 mesh	7.84	2.04	1.97
EC_e:SAR_{ss} :: 8:48	Passed through 16 mesh	8.05	2.13	2.26
EC_e:SAR_{ss} :: 8:48	Passed through 30 mesh	8.08	2.41	2.45

(Farid, 2000)

4.1.6. Heavy metals. Urban agriculture is mainly dependent on the municipal effluent for irrigation those contain variable concentration of different metals in time and space, many of which are essential plant food nutrients. In Pakistan, all the untreated sewage is disposed into rivers or canals through small drains from where water effluent is diverted for irrigation. In spite of this fact, relatively very little work is reported on this issue. From the available findings (Ibrahim & Salmon, 1992; Ali, 1997; Ghafoor *et al.*, 1994a, 1995, 1996, 2001a; Qadir *et al.*, 1999, 2000a), it is concluded that effluent treatment at source is the best and more feasible method to decrease the heavy metal pollution load of city effluent. Alternatively, contaminated soils could be decontaminated through bio-remediation, i.e., growing plants with metal accumulating genetic make up or growing plants those selectively eliminate these metals at root level or those not directly used as animal food. This area is very rich for future research.

5. ACIDS, ACID FORMERS AND GYPSUM USE IN SOIL RECLAMATION

Salt-affected is a general term indicating excess of salts, which are harmful and even toxic to crop plants. Considering the type of salts, these are classified as saline, saline-sodic, sodic, high B, high Mg and acid sulphate soils, although later three categories have minor extent and are practically unimportant.

5.1. Saline soils. Such soils have $EC_e \geq 4$ dS m^{-1}, SAR < 13.2, ESP < 15 and pH_s < 8.5 but generally > 7.0. Osmotic effect regarding the plant water availability is the common problem for crops. In addition, specific ion toxicity as well as induced imbalances in nutrient assimilation by or availability to plants could be another common phenomena. Simple leaching is the reclamation option without any amendment. These soils can also be colonized through the cultivation of high salt tolerant plants (trees and field crops). For details, readers are referred to US Salinity Lab. Staff (1954), Bresler *et al.* (1982), Abrol *et al.* (1988), Rhoades (1982), Ayers and Westcott (1985), Gupta and Gupta (1997), Qureshi and Barret-Lennard (1998), Oster and Jayawardane (1999) and Qadir *et al.* (2000b).

5.2. Saline-sodic soils. These soils have $EC_e \geq 4.0$ dS m^{-1}, SAR ≥ 13.2 and ESP ≥ 15.0. Now-a-days, pH_s is not considered a meaningful parameter for such soils. These soils generally have low HC, low infiltration, and high crust, hard-setting and soil strength if EC_e is not abnormally high as is the case with most of the soil in the gangetic plains. Such soils need Ca^{2+} source (direct or indirect) followed by leaching with any type of water to start with but later, gradually better quality water will be required. High EC_e, Na^+ and waterlogging tolerant field crops would better suit during early phase of reclamation (US Salinity Lab. Staff, 1954; Qureshi & Barret-Lennard, 1998; Qadir *et al.*, 2000b).

5.2.1. Optimum Ca^{2+} concentration for Na-Ca exchange. Gypsum affects reclamation of saline-sodic/sodic soils relatively over a longer period compared to acids (Muhammed & Khaliq, 1975; Ghafoor & Muhammed, 1981; Oster, 1982; Ghafoor *et al.*, 1986, 1997a & b) but much earlier than that achieved by growing salt tolerant plants alone. However, it has been noted that even from soil-applied gypsum @ soil or water GR, considerable un-reacted Ca^{2+} passed through soils into tailoring soil solution below the zone receiving gypsum (Ghafoor *et al.*, 1988; Murtaza *et al.*, 1998), quantity of such calcium may increase if higher soluble Ca^{2+} is made available in soil solution through the application of acids because of dynamic equilibrium prevailing in soils (Lindsay, 1979). The rate limiting factor for Na-Ca exchange is the low CEC of Pakistan soils (8-12 $cmol_c$ kg^{-1}) because of the dominance of illite type clay minerals (Anonymous, 1986; Ranjha *et al.*, 1993). Hence amendments releasing Ca^{2+} slowly like gypsum has been found more promising and effective for Na-Ca exchange. In investigations on a variety of soils, the most efficient Ca^{2+} concentration for Na-Ca exchange has been found 6-10 $mmol_c$ L^{-1} in soil solution and/or irrigation water (Ghafoor & Salam, 1993; Ghafoor, 1999; Murtaza *et al.* 1999). Moreover, sodicity of soils, i.e., high Na^+ accompanied with Cl^- could increase gypsum dissolution. Huges (1979) recorded Ca^{2+} concentration up to 70 $mmol_c$ L^{-1} from saturated solution of gypsum at 25^0C in 6 N NaCl solution. Ghafoor *et al.* (1988b) found gypsum solubility up to 31 $mmol_c$ L^{-1} in NaCl solution of 12 dS m^{-1} EC which decreased to 24 $mmol_c$ L^{-1} in solution of the same EC with SAR of 61 achieved by using mixture of salts, i.e., NaCl, Na_2SO_4, $CaCl_2$ and $MgSO_4$ (Ghafoor & Zubair, 1992). On similar grounds, Mace *et al.* (1999) concluded that H_2SO_4 should be applied only to high CEC soils to get better reclamation because acids cause super-saturation of Ca^{2+} in soil solution with respect to gypsum solubility, i.e., more Ca^{2+} from which lot of un-reacted Ca^{2+} could leach. Frankel *et al.* (1989) observed that mixed application of gypsum and acids resulted in better and faster desorption of Na^+ in saline-sodic soils than either applied alone.

5.2.2. Historical perspectives of using acids in agriculture. Acids can be used for reclaiming only calcareous saline-sodic and sodic soils otherwise lime has to be applied as well. The application of acids is risky and corrosive to farm implements etc. The literature shows that first time, acid (H_2SO_4) was used in crop husbandry in 1916 (Lipman *et al.*, 1916). During the following years, extensive experimentation was conducted in various parts of the world on the use of acids and acid formers (Thorne, 1944; Olson, 1950; Kelly, 1950; Meller, 1956; Sengupta & Cornfield, 1966; Gupta & Veinot, 1974; Manukyan, 1976; Wallace *et al.*, 1976; Ryan *et al.*, 1975a & b; Miyamato *et al.*, 1975, 1977; Stroehlein *et al.*, 1978; Ryan & Stroehlein, 1973, 1979; Rashid & Hamid, 1979; Ghafoor & Muhammed, 1981; Ghafoor *et al.*, 1986, 1997; Brauen *et al.*, 1997). Important chemical reactions of an acid in calcareous saline-sodic/sodic soils are:

$CaCO_3 + H_2SO_4 = 2Ca(HCO_3)_2 + CaSO_4$ -------------(6)

$Ca(HCO_3)_2 + H_2SO_4 = CaSO_4 + 2H_2O + 2CO_2$ ----(7)

$NaX + CaSO_4.2H_2O = Ca_{1/2}X + Na_2SO_4$ ---------(8)

$NaX + H_2SO_4 = H_2X + Na_2SO_4$ ----------------(9)

Newly formed or applied $CaSO_4$ could under go the following chemical reactions to form even lower solubility compounds depending upon the effects of soil-water-plant-atmospheric temperature system:

$CaSO_4.2H_2O + Na_2CO_3 = CaCO_3 + Na_2SO_4$ ----(10)

$CaSO_4.2H_2O + 2MgCO_3 = CaCO_3 + MgSO_4$ ----(11)

Acids could affect soil reclamation at rates faster than that with gypsum, sulphur, pyrite or calcium poly-sulphide. The important discouraging aspect has been and is its high cost and handling hazards. Ghafoor *et al.* (1981, 1986) reported that sulphuric acid application was 5-8 times expensive than gypsum while corresponding value for HCl was higher by 10 times. For many experiments, economics of the treatments has not been reported (Manukyan, 1976; Mace, 1999; Kahloon *et al.*, 2000). Some of the results pertaining to the economics are given in Tables X and XIII.

5.2.3. Gypsum application. For Pakistan soils, gypsum requirement (GR) determined following methods of ESP (US Salinity Lab. Staff, 1954), Schoonover's (Schoonover, 1952) or Schofield and Taylor (1961) was almost similar (Ghafoor *et al.*, 1990). However, method of Chuhan and Chuhan (1984) resulted in lower GR of Indian soils compared to that with the former three methods, since there is a considerable concentration of CO_3^{2-} and HCO_3^- ions in soil solution along with surface alkalinity, which are not to that extent in Pakistan soils. Therefore, leaching prior to gypsum incorporation into plough layer of saline-sodic soils of Pakistan does not appear of any practical significance. Gypsum ($CaSO_4.2H_2O$) is a neutral salt of Ca^{2+} and God has blessed Pakistan with 3.5 billion tons of rock gypsum having purity of $\geq 85\%$ in the salt-range area of Punjab (NFC, 1979) from where it is mined and powdered for agricultural uses. It has low solubility of 28 $mmol_c\ L^{-1}$ at 25°C and in soils seldom exceeds 15 $mmol_c\ L^{-1}$ (Rhoades, 1982) as a result of the above reactions (10) and (11). However, it has low dissolution but effectively sustain the electrolyte concentration for longer periods, which in turn, is very useful for water conducting characteristics of soils (Muhammed & Khaliq, 1975; Frankel *et al.*, 1978; Ghafoor *et al.*, 1989; Baumharat *et al.*, 1992; Raza *et al.*, 2000). Its easy and local availability at low rates and non-hazardous nature are the main reasons of its popularity among our local farmers. Particle size has economic considerations since grinding to finer size-grades becomes expensive compared to coarser size-grades. It has been found that gypsum passed through 16 mesh can reclaim soils very effectively if brackish water is being used for irrigation of soils (Table XVI; Ghafoor *et al.*, 1989; Farid, 2000). Generally, gypsum passed through 30 mesh sieve is considered better (Malik *et al.*, 1984) and same is supplied in bags and in bulk to farmers in Pakistan.

In Pakistan, Malik *et al.* (1984) conducted 55 experiments on different soils, five in each of the 11 districts of Punjab province of Pakistan. They have reported value-cost ratio of 1.8 to 4.6 for crops like rice, wheat, berseem and cotton. Ghafoor and Muhammed (1981) and Ghafoor *et al.* (1997b, 1998) found acids 5 to 10 times expensive than gypsum. Yadav (1973) and Bhatti (1986) also concluded sulphuric acid not to be cost-effective. In India, gypsum has been and is being supplied at nominal rates to farmers in time and space owing to its safe use, being cheap and because of its prolonged effects on water conducting properties of soils (Yadav, 1973). Even the physical presence of gypsum in soils lowers crust, hard-setting and soil strength (Rehman & Rowel, 1979; Simson *et al.*, 1979; Ayers & Westcott, 1985) to favour seed germination (Hassan, 2000) which is one of the greatest problem in salt-affected soils.

CONCLUSIONS

Water quality parameters include EC for total soluble salts, while SAR and RSC reflect the sodicity hazards. The ground/drainage waters and sewage become hazardous because of high EC (> 1.0 dS m^{-1}), SAR (> 10.0) and/or RSC (> 2.5 $mmol_c\ L^{-1}$). For lowering high EC of water, only dilution with low electrolyte water is the option but use of any amendment (gypsum, acids, acid formers) will increase it further without any beneficial effect. To lower high SAR_{iw}, gypsum is the most economical amendment, dilution will decrease it by the square root times of the dilution factor, while use of any acid (sulphurous or sulphuric acid) or acid formers (sulphur, calcium polysulphide etc.) has to do nothing with high water

SAR rather may deteriorate the soil health (physically and chemically) if the later materials are used for longer periods. For high RSC, dilution with low CO_3^{2-} + HCO_3^- water will decrease it proportionately to the dilution factor, Ca-salts will increase Ca^{2+} + Mg^{2+} to affect a decrease in water RSC, while acids or acid formers will decrease water RSC through neutralizing the CO_3^{2-} + HCO_3^-. Among RSC treatments, gypsum is economical and safe, although acids could accomplish the same but at a much higher cost.

For reclaiming saline soils ($EC_e \geq 4.0$ dS m^{-1}, SAR # 13.0), no amendment is required rather simple leaching with all the types of water (canal, ground water, agricultural drainage) is useful at the beginning following a gradual shift towards sweet water application. For saline-sodic ($EC_e \geq 4.0$ dS m^{-1}, SAR ≤ 13.0) and sodic ($EC_e \leq 4.0$ dS m^{-1}, SAR ≥ 13.0) soils, Ca-carriers (gypsum, calcium chloride, calcium nitrate, phosphogypsum) are economical, while acids (H_2SO_4, HCl, HNO_3) or acid formers (sulphur, calcium poly-sulphide, pyrite, ferrous sulphate) can reclaim such soils relatively at a faster rate but at a 5-10 times higher cost. However, import of technology pertaining to amelioration of brackish waters and salt-affected soils through acids without testing under local soil and water conditions may not prove sustainable.

Based upon the literature, the most feasible cropping systems are: rice (*Oryza sativa* L) - wheat (*Triticum aestivum* L) in the upper Punjab (i.e. rice areas) and rice-berseem in the central and southern Punjab (mix cropping and cotton-wheat areas). Inclusion of junter (*Sesbania aculeata*) as fodder or green manure crop will be helpful in soil reclamation and Kallar grass (*Leptochloa fusca*) is also a good summer fodder crop for very high EC and SAR soils during the initial years even using very poor quality waters for irrigation.

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