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FRACTIONATION AND DISTRIBUTION OF IRON IN THE SALT-AFFECTED SOILS OF MUKTSAR DISTRICT OF PUNJAB

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ABSTRACT

Nine salt-affected soils from Muktsar district of Punjab were studied for distribution of the chemical forms of iron in relation to changing soil properties for predicting the iron behavior in the soil-plant system. Except for iron associated with crystalline Fe-oxides (CFeOX) and residual fraction (RES), all other fractions constituted less than one per cent of the total soil iron. Iron in Mn-oxides (MnOX), amorphous Fe-oxides (AFeOX) and crystalline Fe-oxides occurred in the ratio 1:15:164. The plant-available DTPA fraction and organically bound Fe (OM-Fe) have the lowest content in the sodic soils due to higher pH and lower organic matter content. The clay fraction showed greater influence on specifically adsorbed (SpAd) and residual (RES) iron fractions in the saline-sodic soils due to its higher content. The DTPA- Fe was significantly and positively correlated with OC, MnOX-Fe and AFeOX-Fe. The soil pH negatively correlated with WSEX-Fe and DTPA-Fe as indicated by higher "r" values. An increasing trend of total Fe down the depth in some soils suggested its translocation/ illuviation in subsurface horizons. The sodic soils thus needs better managements because of constraints in some physico-chemical properties and fertility aspects.

KEY WORDS
Physico-chemical characteristics, Iron fractions, Profile distribution, Salt-affected soils

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INTRODUCTION

The salinity and sodicity are the serious problems in arid and semi-arid regions of the world particularly for agricultural production. Per capita land resources are shrinking with ever increasing population pressure. This resource is becoming degraded at an increasing rate due to soil salinity/alkalinity, waterlogging and soil pollution. The shrinking of agricultural land and the demand for more food production calls for multiple cropping in a single piece of land (Singh *et al.,*2014). Adoption of reclamation technology for salt-affected soils in Punjab long back has reduced its area from 0.7 m ha in 1972 to 0.152 m ha in 1996 (Sharma *et al.,* 1996). Now, out of the total geographical area 5.03 m ha, about 0.06 m ha of land is still affected with salinity or sodicity in Punjab (Sharma *et al.,* 2009). Soil fertility depends upon the presence of essential nutrients in adequate amount and its availability, but there may be other factors like physical condition of soil, environmental condition etc affecting it (Rai, 2002). Micronutrients like B, Cu, Zn, Mn, Fe, Mo etc. are essential for plant growth and plant health, and required at very low level. Among the various micronutrients, iron is an important element required for crop production. Most soils contain an abundance of total Fe, but many interacting factors affect and limit the Fe availability. In Punjab, Fe is considered to be the second most limiting micronutrient in crop production after Zn. Iron deficiency is widespread in crops grown on coarse-textured and calcareous soils. Considering 4.5 ppm DTPA extractable Fe as the critical limit, about 12% of soils of Punjab are deficient in Fe. Iron deficiency is widespread in Inceptisols and Aridisols, especially in calcareous high pH soils, compact soils, which restrict aeration (Muralidharudu and Raj, 2004). Sharma *et al.* (2009) found decreased activity of micronutrients Zn, Mn, Cu and Fe in salt-affected soils of North-western India due to high pH and EC resulting in their low availability, and thus causing a major constraint for crop production. The low organic matter content because of the prevailing arid and semiarid climatic conditions further accentuates the limited availability of micronutrients. Understanding the mechanism of distribution of Fe in different fractions helps to know its retention in soils and release to plants. The nature and amount of the various forms of Fe depends upon the variation in soil texture, pH, calcium carbonate, organic matter and other soil characteristics (Saini *et al.,* 1995).

Realizing the seriousness of the problem and optimizing productivity, the present investigation was undertaken to study physico-chemical characteristics and distribution of different forms of iron in the salt-affected soils.

MATERIALS AND METHODS

This study was designed with the objective to determine the status and distribution of iron in salt-affected soils of Muktsar district of Punjab. The study area falls in extending between the latitudes of 29°52' and 32°32' N and longitudes of 73°52' and 76°56' E. The major parts of the area have an aridic (torric) moisture regime whereas the soil temperature regime is hyperthermic according to the criteria of soil taxonomy (Soil Survey Staff., 1998). A total of nine profiles (P1 to P9) were exposed based on several traverses and field observations from different parts of the Muktsar district. Three profiles P1, P4 and P5 belong to saline soils, other three profiles P3, P6 and P9 belong to sodic soils, and four profiles (P2, P7, P8 and P10) represent the saline-sodic soils. These profiles were exposed from 150 to 200 cm and described for morphological properties in the field (Soil Survey Staff., 1951). The six soil samples were collected from each of the morphologically differentiated horizon in each soil profile. All samples were dried, ground with wooden mottle and passed through 2mm sieve. After sieving all the samples were packed in the polythene bags for laboratory investigations.

The various physico-chemical properties were determined following the standard procedures as described by (Richard, 1954). The soil reaction and electrical conductivity were determined in (1:2) soil: water suspension with the help of glass electrode pH meter and conductivity meter, respectively. Mechanical analysis was done adopting International Pipette method (Page *et al* 1982). Organic Carbon (OC) was estimated by wet digestion method (Walkley and Black, 1934) whereas calcium carbonate by rapid titration method (Puri, 1930). The rapid method for simultaneous determination of exchange capacity and exchangeable cations was applied as described by (Belyayeva, 1967). DTPA-extractable Fe was determined according to the method developed by (Lindsay and Norvell, 1978). Total Fe was determined using Aqua regia-HF-HNO3 and HCl, according to method outlined by (Shuman, 1988). A seven step sequential fractionation procedure was followed to partition Fe into Water soluble plus exchangeable Fe (WSEX-Fe), Specifically adsorbed Fe (SpAd-Fe), Mn-oxide bound Fe (MnOX-Fe), Amorphous Fe-oxides bound Fe (AFeOX-Fe), Crystalline Fe-oxides bound Fe (CFeOX-Fe), Organically bound Fe (OM-Fe) and Residual Fe (RES-Fe).

RESULTS AND DISCUSSION

Physico-chemical characteristics of the soils

Saline soils

The saline soils showed varied texture as loam, silt loam or sandy loam. The mechanical composition of the soils revealed the sand content varying from 6.9 to 68.4 per cent (mean = 40.4 %) whereas the silt and clay contents were in the range of 20.6 to 83.7 per cent (mean = 45.9 %) and 8.2 to 21.6 per - cent (mean = 13.6 %), respectively (Table 1). The soils were high in silt and clay contents together suggesting dominance of finer fractions. The surface horizon showed pH from 8.6 to 8.9 whereas subsurface horizons had pH ranging from 8.3 to 10.2 (mean = 9.0). No definite trend of pH with depth was observed in these soils. The high pH may be due to liberation of free OH^- ions as a result of hydrolysis and desiccation of calcium carbonate (Lloyed and Peterson, 1964). Electrical conductivity varied from 1.23 to 19.1 dS m^{-1} having the highest in P4 soil (mean = 7.69 dS m^{-1}) suggesting accumulation of salts in the soils. Organic carbon content varied very widely (0.02 to 0.87 %) having higher content in the surface horizon than in the subsurface horizon. Calcium carbonate content varied from 2.1 to 19.6 per cent showing increasing trend with depth. In general, its content is higher in the horizons

Table 1: Range and mean values of some selected properties of the salt-affected soils

Parameter	Sand (%)	Silt (%)	Clay (%)	pH (1:2)	EC (dS m^{-1})	OC (%)	$CaCO_3$ (%)	CEC (cmol kg^{-1})
Profile 1 (Saline)								
Range	6.9-41.3	44.3-83.7	8.2-14.4	8.8-10.2	1.23-14.50	0.32-0.87	3.3-19.6	5.63-8.03
Mean	25.4	63.3	11.3	9.6	4.06	0.53	12.3	6.40
Profile 4 (Saline)								
Range	47.2-68.4	20.6-35.3	11.0-21.6	8.3-8.6	4.71-19.10	0.04-0.26	3.3-9.3	5.55-7.77
Mean	54.9	29.7	15.5	8.5	7.69	0.10	5.8	6.39
Profile 5 (Saline)								
Range	30.5-48.1	38.1-57.7	10.6-18.6	8.6-9.0	2.73-4.96	0.02-0.28	2.1-9.7	4.51-6.27
Mean	40.9	44.9	14.2	8.8	4.00	0.11	6.3	5.62
Profile 3 (Sodic)								
Range	27.0-74.2	21.8-66.2	4.2-25.0	9.1-10.0	0.44-3.87	0.14-0.23	1.3-18.9	5.57-9.76
Mean	51.9	39.5	8.6	9.6	2.24	0.18	8.4	6.39
Profile 6 (Sodic)								
Range	23.6-50.9	43.7-64.5	5.4-27.6	8.6-8.9	0.47-2.08	0.01-0.29	5.0-19.4	5.35-7.09
Mean	31.9	52.9	15.2	8.8	1.36	0.08	12.0	6.12
Profile 8 (Sodic)								
Range	3.7-31.8	65.6-92.9	1.8-3.4	8.7-9.9	0.31-2.25	0.02-0.18	1.2-15.4	5.22-7.26
Mean	21.7	75.7	2.6	9.3	0.83	0.06	6.4	6.09
Profile 2 (Saline-sodic)								
Range	43.5-50.8	38.0-45.7	6.6-13.6	8.7-9.4	0.55-2.45	0.25-0.68	0.6-5.0	4.64-6.28
Mean	46.0	42.5	11.5	9.0	1.49	0.38	1.9	5.74
Profile 7 (Saline-sodic)								
Range	7.6-27.8	68.5-80.4	3.2-12.0	8.6-8.8	2.67-11.80	0.01-0.17	5.8-17.1	4.64-7.11
Mean	20.7	71.9	7.4	8.7	4.71	0.05	12.3	5.52
Profile 9 (Saline-sodic)								
Range	24.7-30.9	66.7-71.9	1.6-4.0	8.4-9.0	3.11-9.70	0.13-0.18	2.35-4.30	5.23-7.11
Mean	27.1	63.5	2.7	8.8	4.68	0.16	3.48	6.51

Table 2: Vertical distribution of Fe fractions in the saline soils

Depth(cm)	DTPAFe mg kg^{-1}	WSEX Fe	SpAdFe	MnOX Fe	AFeOXFe	CFeOX Fe	OMFe	RESFe	Total Fe (%)
Profile 1									
0-19	10.62	0.16	0.29	22.7	344.8	3325.2	195.0	1.74	2.13
19-30	2.96	0.19	0.89	7.9	109.8	3736.4	124.4	1.81	2.18
30-52	2.24	0.18	1.37	2.6	43.6	893.2	121.4	2.27	2.39
52-83	2.08	0.20	0.74	99.9	1040.4	1089.2	119.2	2.26	2.50
83-110	1.84	0.16	0.39	1.7	516.0	208.8	15.8	2.07	2.15
110-150	1.70	0.01	0.34	5.1	56.6	292.0	420.2	2.07	2.15
Mean	3.57	0.15	0.67	23.3	351.9	1590.8	166.0	2.03	2.25
Profile 4									
0-17	31.2	0.01	0.37	72.9	459.0	1690.0	208.4	1.69	1.94
17-36	3.38	0.42	0.79	9.4	83.4	2890.8	114.8	1.61	1.93
36-51	2.12	0.09	0.54	2.7	84.0	2352.4	223.4	2.17	2.44
51-68	2.82	0.04	0.27	6.8	70.4	1802.0	134.6	1.71	1.92
68-90	1.82	0.04	1.38	1.3	29.8	576.8	381.4	2.34	2.45
90-125	2.50	0.02	0.71	1.8	40.4	2191.6	90.6	1.94	2.18
Mean	7.30	0.10	0.68	15.8	127.8	1917.3	192.2	1.91	2.14
Profile 5									
0-14	7.92	0.22	0.67	7.2	142.4	841.6	138.4	2.18	2.29
14-30	1.50	0.27	1.06	3.4	39.8	701.6	106.4	2.02	2.10
30-45	1.46	0.18	1.39	2.7	30.4	3279.2	155.0	1.69	2.04
45-66	1.76	0.16	0.15	10.9	82.4	3818.0	297.0	1.73	2.16
66-90	1.96	0.47	0.41	7.0	83.2	635.2	148.0	2.53	2.62
90-120	2.06	0.19	0.22	1.4	35.0	1430.0	60.4	2.17	2.32
Mean	2.78	0.25	0.65	5.4	68.9	1784.3	150.9	2.05	2.25

Table 3: Vertical distribution of Fe fractions in the sodic soils

Depth(cm)	DTPAFe mg kg^{-1}	WSEX Fe	SpAdFe	MnOX Fe	AFeOXFe	CFeOX Fe	OMFe	RESFe	Total Fe (%)
Profile 3									
0-16	3.12	0.31	0.45	9.9	342.8	2924.8	162.2	1.86	2.20
16-42	5.80	0.13	0.41	18.4	527.4	3020.4	253.8	1.11	1.49
42-60	1.60	0.24	1.21	2.1	49.0	1030.4	53.0	1.16	1.28
60-85	1.14	0.11	1.30	1.3	49.2	360.0	99.6	1.97	2.03
85-100	1.70	0.21	0.71	1.2	78.8	545.2	68.4	2.09	2.16
100-125	1.38	0.13	0.81	1.8	17.4	179.6	19.6	1.93	1.96
Mean	2.46	0.19	0.82	5.8	177.4	1343.4	109.4	1.68	1.85
Profile 6									
0-18	3.20	0.44	0.47	5.7	77.6	228.4	140.6	1.91	1.96
18-50	2.02	1.24	0.96	1.8	32.0	202.8	15.0	2.45	2.48
50-70	2.06	0.12	0.75	1.2	22.4	345.6	232.8	2.76	2.82
70-86	2.40	0.52	0.22	3.9	55.6	849.6	22.6	2.04	2.14
86-106	1.94	0.68	0.94	1.9	73.4	976.4	146.6	2.30	2.43
106-130	1.80	0.04	0.62	7.3	167.6	1634.4	82.2	2.13	2.32
Mean	2.24	0.51	0.66	3.6	71.4	706.2	106.6	1.98	2.36
Profile 8									
0-18	1.54	0.47	0.08	5.3	76.4	628.8	304.2	1.71	1.81
18-38	1.08	0.05	0.20	8.7	162.4	2288.4	328.0	1.09	1.37
38-68	1.40	0.23	0.25	8.9	179.0	2651.4	308.0	1.33	1.65
68-80	1.24	0.32	0.20	8.6	82.2	2415.6	414.0	1.34	1.64
80-96	1.38	0.60	0.33	2.3	64.5	2271.6	75.0	2.60	2.85
96-128	2.26	0.47	0.14	4.3	50.6	252.4	50.4	2.83	2.87
Mean	1.48	0.36	0.20	6.4	102.5	1751.4	246.6	1.82	2.03

having finer texture (Young and Spycher, 1979). The soils exhibited cation exchange capacity varied from 4.51 to 8.03 cmol (+) kg^{-1} which could be due to high silt content which contributes little to negative charge in soils.

Sodic soils

The soils showed varied textures as silty clay loam, silt, silt loam, loam and sandy loam. On mean basis, the sodic soils contained 35.1 per cent sand, 56.0 per cent silt and 8.8 per cent clay fractions (Table 1). The sodic soils are highly alkaline in reaction with pH ranging from 8.6 to 10.0 having higher pH even in surface horizons. The electrical conductivity values are relatively lower compared to the saline soils due to low amounts of soluble salts. The sodic soils had low organic carbon content as compared to the saline soils which varied

Table 4: Vertical distribution of Fe fractions in the saline-sodic soils

Depth(cm)	DTPAFe mg kg^{-1}	WSEX Fe	SpAdFe	MnOX Fe	AFeOXFe	CFeOX Fe	OMFe	RESFe	Total Fe (%)
Profile 2									
0-18	5.08	0.25	0.23	23.1	340.8	2551.6	337.8	1.66	2.01
18-40	2.14	0.19	0.52	17.8	239.4	2410.8	483.4	1.82	2.14
40-57	2.20	0.09	0.59	12.6	173.4	2996.4	238.4	1.73	2.09
57-82	2.18	0.24	0.52	12.8	170.2	2520.4	282.2	1.81	2.11
82-110	2.22	0.12	0.49	10.6	270.8	3122.4	381.4	1.89	2.27
110-130	2.62	0.06	0.51	5.9	47.2	3136.0	31.8	1.76	2.09
Mean	2.74	0.16	0.48	13.8	206.9	2789.6	292.5	1.78	2.12
Profile 7									
0-16	1.50	0.08	0.74	6.3	32.8	3427.2	224.6	1.56	1.93
16-28	1.38	0.01	0.20	5.9	49.4	1238.4	213.8	1.95	2.11
28-42	1.58	0.08	0.72	2.3	37.4	1797.2	160.0	1.82	2.02
42-70	1.46	0.04	0.29	1.6	27.2	1042.0	19.4	2.00	2.11
70-105	1.68	0.06	1.18	1.5	36.4	334.8	106.4	2.09	2.14
105-125	2.50	0.05	0.74	2.1	41.4	399.2	30.6	2.83	2.88
Mean	1.68	0.05	0.65	3.3	37.4	1373.1	125.8	2.04	2.19
Profile 9									
0-15	10.26	0.25	0.21	20.1	379.0	283.2	677.0	1.86	1.99
15-24	6.06	0.13	0.19	18.6	358.2	2556.4	345.0	1.65	1.98
24-38	2.58	0.13	0.18	5.9	154.2	3267.6	330.8	1.25	1.63
38-60	2.92	0.14	0.25	5.5	228.2	2883.6	346.8	1.34	1.69
60-120	6.22	0.27	0.22	18.0	354.4	2304.0	303.6	1.39	1.69
120-140	18.92	0.20	0.32	34.1	152.4	2029.6	66.8	1.56	1.79
Mean	7.83	0.19	0.23	17.0	271.1	2220.7	345.0	1.50	1.79

Table 5: Correlation between forms of Fe and physico-chemical properties of saline soils

Saline soils	Sand	Silt	Clay	pH	EC	OC	$CaCO_3$	CEC
DTPA	0.312	-0.233	-0.238	-0.197	0.888*	0.202	-0.301	0.048
WSEX	0.147	-0.112	-0.105	0.118	-0.228	-0.026	-0.203	-0.150
SpAd	0.212	-0.197	0.023	0.101	-0.266	0.042	0.105	0.301
MnOX	-0.081	0.121	-0.233	0.320	0.372	0.270	0.164	-0.063
AFeOX	-0.352	0.402	-0.402	0.512*	0.139	0.389	0.443*	-0.081
CFeOX	0.459*	-0.463*	0.231	-0.272	0.310	0.250	-0.631*	-0.007
OM	-0.076	0.032	0.182	-0.125	0.105	-0.074	-0.068	0.264
RES	-0.410	0.375	-0.015	0.356	-0.493*	-0.183	0.355	0.049
Total	-0.318	0.272	0.079	0.370	-0.439	-0.067	0.155	0.076
Sodic soils								
DTPA	0.593*	-0.575*	0.010	-0.366	-0.330	0.456*	-0.235	0.048
WSEX	-0.331	0.204	0.267	-0.367	-0.271	-0.123	0.432	-0.195
SpAd	0.226	-0.327	0.256	0.130	0.669*	0.194	0.334	0.022
MnOX	0.557*	-0.342	-0.452*	-0.106	-0.473*	0.173	-0.676*	-0.127
AFeOX	0.717*	-0.555*	-0.314	-0.037	-0.344	0.286	-0.579*	0.016
CFeOX	0.388	-0.169	-0.475*	0.005	-0.471*	-0.151	-0.616*	-0.109
OM	0.123	0.060	-0.417	0.117	-0.384	-0.069	-0.819*	-0.265
RES	-0.539*	0.340	0.415	-0.430	-0.136	-0.241	0.662*	0.171
Total	-0.505*	0.337	0.345	-0.481*	-0.270	-0.300	0.580*	0.162
Saline-sodic soils								
DTPA	-0.044	0.162	-0.406	0.164	0.157	0.053	-0.238	0.284
WSEX	0.282	-0.233	-0.013	0.180	0.035	0.614*	-0.653*	0.035
SpAd	-0.166	0.003	0.448*	0.025	-0.054	-0.232	0.548*	-0.437
MnOX	0.345	-0.259	-0.104	0.282	0.030	0.469*	-0.618*	0.288
AFeOX	0.265	-0.198	-0.086	0.216	0.032	0.450*	-0.687*	0.220
CFeOX	0.654*	-0.528*	-0.072	0.244	-0.120	0.460*	-0.712*	0.358
OM	0.234	-0.165	-0.107	-0.036	0.326	0.328	-0.632*	0.037
RES	-0.365	0.143	0.532*	0.023	-0.156	-0.258	0.664*	-0.217
Total	-0.170	-0.055	0.643*	0.134	-0.230	-0.095	0.486*	-0.118

Crtical value of r at 5% = 0.443 and * indicates significant value

from 0.01 to 0.29 per cent. Calcium carbonate content varied from 1.3 to 19.4 per cent and the trend was irregular with depth in the soils. The soils did not vary much in cation exchange capacity which ranges from 5.22 to 7.36 cmol(+) kg^{-1}.

Saline-sodic soils

The saline-sodic soils showed consistency in texture with

Table 6: Correlation between Fe fractions and physico-chemical properties in all the soils

	Sand	Silt	Clay	pH	EC	OC	$CaCO_3$	CEC
All salt-affected soils								
DTPA	0.185	-0.134	-0.081	-0.145	0.642*	0.258*	-0.207	0.036
WSEX	-0.106	0.042	0.145	0.05	-0.267*	-0.069	0.185	-0.029
SpAd	0.141	-0.223	0.283*	0.175	-0.036	0.035	0.342*	-0.014
MnOX	0.084	-0.047	-0.076	0.138	0.343*	0.330*	-0.117	-0.017
AFeOX	0.066	0.003	-0.175	0.263*	0.123	0.409*	-0.107	-0.039
CFeOX	0.379*	-0.273*	-0.172	-0.157	0.117	0.261*	-0.597*	-0.008
OM	0.077	0.021	-0.255*	-0.222	0.201	0.081	-0.588*	0.034
RES	-0.124	-0.018	0.363*	0.203	-0.145	-0.142	0.159	0.319*
Total	-0.283*	0.095	0.440*	-0.069	-0.105	-0.028	0.464*	0.021

Crtical value of r (5%) = 0.250 and * indicates significant value

depth suggesting deposition of uniform parent material of the soils. The profile 2 had loam texture whereas profiles 7 and 9 invariably had silt loam texture. The particle size distribution of the saline-sodic soils revealed sand content varying from 7.6 to 50.8 per cent, silt content from 38.0 to 80.4 per cent and clay content from 1.6 to 13.6 per cent (Table 1). The soils are alkaline in reaction with pH ranging from 8.4 to 9.4 showing relatively higher pH in the lower horizons. The presence of salts, calcium carbonate and sodium carbonate may have resulted for moderate pH in the soils. The electrical conductivity ranged from 0.55 to 11.8 dS m^{-1} indicating deposition of salts in varying amounts in different depths. The electrical conductivity value was lower in these soils as compared to the saline soils but higher compared to the sodic soils. The soils were low to medium in OC (< 0.75 %) which varied from 0.01 to 0.68 per cent. Calcium carbonate content of the saline-sodic soils varied from 0.6 to 17.1 per cent having the highest in P7 soil.

Distribution of different fractions of Fe in the soils

Iron in soils occurs in various chemical fractions associated with soil solution, organic and inorganic solid phases governed by various factors including management practices for cultivation (Sangwan and Singh, 1993 and Bahera *et al.,* 2009). The data on distribution of different fraction of iron in the salt-affected soils is presented in Table 2 to 4. The DTPA extractable Fe (DTPA-Fe) in the different salt-affected soils ranged between 1.08 to 31.2 mg kg^{-1} having the highest in the saline soils (mean = 4.55 mg kg^{-1}) and the lowest in the sodic soils (mean = 2.06 mg kg^{-1}). Sharma and Nayyar, (2004) found DTPA-Fe varying from 1.18 to 32.56 mg kg^{-1} with an average of 10.93 mg kg^{-1} in the soils of Muktsar district of Punjab. The sodic soils belonging to Ustochrepts of Sangrur, Ludhiana, Ferozepur, Faridkot and Bathinda districts have shown higher incidence of Fe deficiency due to higher pH compared to normal soils of other districts (Nayyar *et al.,* 1990). The surface horizons showed relatively higher content of DTPA-Fe than the subsurface horizon may be due to accretion of organic matter at the surface from natural vegetation and crops causing relatively higher extractable values (Sharma *et al.,* 2008). Several studies in the past have reported the highest DTPA-extractable Fe in the surface horizon which decreased with depth (Jalali *et al.,* 1989; Singh *et al.,* 1990; Khan *et al.,* 2002 and Sharma *et al.,* 2005). Water soluble plus exchangeable Fe (WSEX-Fe) in the soils ranged from 0.01 to 0.47 mg kg^{-1} in the saline soils, 0.04 to 1.24 mg kg^{-1} in the sodic soils and 0.01 to 0.27 mg kg^{-1} in the saline-sodic soils with a mean value of 0.17, 0.35 and 0.14 mg kg^{-1}, respectively (Tables 2-4). The sodic soils had higher content of WSEX-Fe may be due to their finer texture. The lower amount of water soluble plus exchangeable Fe may be due to the lower cation exchange capacity of these soils. The low value of WSEX-Fe may also be attributed to the lower amount of organic matter of the soils as studies have reported that the addition of FYM/ organic matter tends to increase the WSEX-Fe content (Maskina *et al.,* 1998 and Hellel, 2007). Water soluble plus exchangeable Fe generally had higher content in surface horizon but no consistent trend with depth was observed. Specifically adsorbed Fe on inorganic sites (SpAd-Fe) in different soils varied from 0.08 to 1.39 mg kg^{-1} with mean content of 0.56 mg kg^{-1}. The saline soils had higher content of specifically adsorbed Fe (mean = 0.67 mg kg^{-1}) followed by the sodic soils (mean = 0.56 mg kg^{-1}) and the saline-sodic soils (mean = 0.45 mg kg^{-1}). Sharma *et al.,* (2008) reported relatively higher content of specifically adsorbed Fe in Aridisols compared to Inceptisols of Punjab. Specifically adsorbed Fe generally increased to some depth in the profiles except in P4, P7 and P9 where it showed irregular pattern. The higher content of specifically adsorbed Fe in saline and sodic soils may be due to higher clay and calcium carbonate contents in these soils.

The results on Fe adsorbed on oxide surfaces (MnOX-Fe, AFeOX-Fe and CFeOX-Fe) in different soils are presented in Tables 2 to 4. The Mn-oxide (MnOX-Fe) bound fraction varied from 1.3 to 99.9 mg kg^{-1} in the saline soils, 1.2 to 18.4 mg kg^{-1} in the sodic soils and 1.5 to 34.1 mg kg^{-1} in the saline-sodic soils with an average value of 14.8, 5.3 and 11.4 mg kg^{-1}, respectively. The amorphous Fe-oxides (AFeOX-Fe) bound fraction varied from 29.8 to 1040.4 mg kg^{-1} in the saline soils, 17.4 to 527.4 mg kg^{-1} in the sodic soils and 27.2 to 379.0 mg kg^{-1} in the saline-sodic soils with an average value of 182.8, 117.1 and 171.8 mg kg^{-1}, respectively. The crystalline Fe-oxides (CFeOX-Fe) bound fraction varied from 208.8 to 3818.0 mg kg^{-1} in the saline soils, 179.6 to 3020.4 mg kg^{-1} in the sodic soils and 283.2 to 3427.2 mg kg^{-1} in the saline-sodic soils with a mean value of 1764.1, 1267.0 and 2127.8 mg kg^{-1}, respectively. The different oxide bound Fe fractions followed the order as MnOX-Fe < AFeOX-Fe < CFeOX-Fe occurring in the ratio of about 1:15:164. Randhawa and Singh (1997) reported that about 41 per cent of the total Fe was associated with CFeOX-Fe fraction. Sharma *et al.* (2008) observed the highest content of different iron fractions in the surface horizon which decreased with depth. The application of FYM seems to increase the amorphous-Fe content but decrease the crystalline-Fe probably due to inhibition of iron crystallization (Agbenin, 2003).

Organically bound Fe (OM-Fe) content ranged between 15.8 and 420.2 mg kg^{-1} in the saline soils (mean = 169.7 mg kg^{-1}), 15.0 and 414.0 mg kg^{-1} in the sodic soils (mean = 154.2 mg kg^{-1}) and 19.4 and 677.0 mg kg-1 in the saline sodic soils (mean = 254.4 mg kg^{-1}) suggesting the highest in the saline-sodic soils and the lowest in the sodic soils. The lowest amount of organically bound Fe in the sodic soils may be due to their low content of organic carbon. Generally, organically bound Fe showed higher content in the surface horizon due to more organic matter.

Residual Fe (RES-Fe) fraction ranged from 1.09 to 2.83 per cent in different salt-affected soils having mean value of 1.99 per cent in the saline soils, 1.83 per cent in the sodic soils, and 1.77 per cent in the saline sodic soils. Singh *et al.,* (1988) and Randhawa and Singh, (1997) reported that about 53 per cent of the total soil Mn and 52 per cent of the total soil Fe are present in residual fraction. Application of FYM in combination with NPK mobilizes non-labile Fe sources into labile and plant available forms (Agbenin, 2003). Total Fe in different soils followed similar trend like residual Fe, having higher content in the saline soils (mean = 2.21 %) followed by the sodic soils (mean = 2.08 %) and the saline-sodic soils (mean = 2.03 %). These values are comparable to those reported by Takkar, (1969) in calcareous soils (1.41 to 2.15 %) of Punjab and Haryana. Sharma *et al.,* (2009) also reported an average value of 1.67 per cent for total Fe content in salt-affected soils of Punjab. The main source of Fe in soils is primary and secondary minerals such as olivine [$(Mg,Fe)_2SiO_4$], siderite ($FeCO_3$), hematite (Fe_2O_3), geothite (FeOOH), and magnetite (Fe_3O_4) (Lindsay, 1979). An increasing trend of total Fe down the depth in some soils apparently suggested illuviation causing higher total Fe in subsurface horizons than in the surface horizons. These findings show a close relationship between soil processes and Fe movement in profiles (Sharma *et al.,* 2002 and Sharma *et al.,* 2005).

Correlation among soil properties and Fe fractions

Correlation matrix between physico-chemical properties and different forms of Fe in different categories of salt-affected soils is presented in table 5. In saline soils the sand fraction showed significant positive correlation (r = 0.459*) and silt fraction significant negative correlation (r = -0.463*) with crystalline Fe-oxides (CFeOX-Fe). Soil pH has not shown any significant relation with DTPA-Fe (r = -0.197) but showed a significant positive correlation with amorphous Fe-oxides (AFeOX-Fe) fraction (r = 0.512*). A decrease in DTPA-Fe with increase in soil pH, however, was reported by Katyal and Sharma, (1979) and Mondal and Meeta, (1991). The effect of EC on DTPA-Fe and RES-Fe was quite evident from the significant positive (r = 0.888*) and negative (r = -0.493*) correlations respectively. Singh and Ram, (2007) reported that the DTPA-extractable Zn, Cu, Fe and Mn were positively and significantly correlated with EC, OC and clay content in soils. Similarly, Elbordiny and Camilia, (2008) reported that the DTPA-extractable Zn, Cu, Fe and Mn were positively correlated with EC and OC in the different soils.

The sand fraction was significantly positively correlated with MnOX-Fe, AFeOX-Fe, RES-Fe and Total-Fe whereas the silt fraction was significantly negatively correlated with AFeOX-Fe in the sodic soils (Table 5). The clay fraction had significant negative correlation with MnOX-Fe (r = -0.452*) and CFeOX-Fe (r = -0.475*). The soil pH appears to have affected negatively on DTPA-Fe and WSEX-Fe more in the sodic soils as indicated by relatively higher "r" values. Electrical conductivity showed significant positive correlation with SpAd-Fe (r = 0.669*) and significant negative correlation with MnOX-Fe (r = -0.473*) and CFeOX-Fe (r = -0.471*). The OC showed significant positive correlation with DTPA-Fe (r = 0.456*). Calcium carbonate showed significant negative correlation with MnOX-Fe, AFeOX-Fe, CFeOX-Fe and OM-Fe fractions, and significant positive correlation with RES-Fe and Total-Fe. It is reported that calcium carbonate retains Zn, Cu, and Mn in their complexes and may cause Fe precipitation (Sharma *et al.,* 2005) which is the reason for deficiency of available micronutrients. In the saline-sodic soils the clay fraction showed greater importance in affecting iron fractions than in other soils may be due to its higher content in these soils. The clay fraction was significantly positively correlated with SpAd-Fe, RES-Fe and Total-Fe. Organic carbon was significantly positively correlated with WSEX-Fe, MnOX-Fe AFeOX-Fe and CFeOX-Fe fractions. Calcium carbonated influences almost every iron fractions except DTPA-Fe in the saline-sodic soils. Like in other soils, the CEC showed non significant correlation with all the forms of Fe in the saline-sodic soils.

The crystalline Fe-oxides (CFeOX-Fe) bound fraction showed significant positive correlation with sand fraction (r = 0.379*) whereas significant negative correlation with the silt fraction (r = -0.273*) suggesting presence of minor amounts of iron minerals in sand fraction but absent in silt fraction. The clay fraction had significant positive correlation with specifically adsorbed Fe (SpAd-Fe), RES-Fe and Total-Fe as also seen in the saline-sodic soils (Table 5). Like in saline soils, pH showed only significant positive correlation with AFeOX-Fe fraction (r = 0.263*). The correlation coefficient data (Table 6) revealed EC significantly positive correlated with the DTPA-extractable Fe (r = 0.642*) whereas significant negative correlation with the WSEX-Fe (r = -0.267*). Organic carbon had significant positive correlation with DTPA-Fe and iron adsorbed on oxide surfaces i.e MnOX-Fe, AFeOX-Fe and CFeOX-Fe fractions. Calcium carbonate showed significant positive correlation with SpAd-Fe and total-Fe fractions, and significant negative correlation with CFeOX-Fe and OM-Fe fractions. Among the different Fe fractions, the DTPA-Fe fraction showed significant positive correlation with MnOX-Fe (r = 0.580*) and AFeOX-Fe bound fraction (r = 0.343*). However, the significant negative correlation was observed between WSEX-Fe and CFeOX-Fe (r = -0.237*), SpAd-Fe and CFeOX-Fe (r = -0.251*) and CFeOX-Fe and total Fe (r = -0.349*).

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APPLICATION FORM

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