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Forms of sulphur and their relationship with soil properties in some soils of North Bank Plain zone of Assam

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Abstract : Forms of sulphur and their relationships with soil properties and sulphur availability indices were investigated in some rapeseed-growing Inceptisols of Lakhimpur, Sonipat and Darrang districts, Assam. The abundance of various forms of sulphur was in the decreasing order *i.e.* total S >organic S (83.12-87.17%) > heat soluble S (4.78-6.12 %) >sulphate S> water soluble S> adsorbed S. All forms of S showed significantly positive correlation with organic carbon and clay content. The significant correlation between different forms of S suggested an interrelated dynamic equilibrium among different forms of S. Organic carbon was the most dominant factor governing the Sulphur Availability Index (r = 0.795**) followed by clay (r = 0.672**). The step-wise multiple regression analysis revealed that organic carbon and clay play an important role towards different forms of S and sulphur availability index. About 28 and 40 per cent of soils of Lakhimpur and Darrang district were found deficient in available S.

Additional key words : *Forms of sulphur, sulphur availability index, soil properties*

Introduction

Sulphur (S) is the fourth major plant nutrient whose deficiency is widespread in India and considered as quality and quantity limiting factors particularly for oilseed crops. The data generated by the ICAR project and the TSI-FAI project reported that 46 per cent samples were deficient in S and another 30% samples were medium in available S which could be considered as potentially S deficient (Tandon and Messick 2007). Oilseed crops are extensively grown in an area of 3.08 lakh ha of Assam representing Entisols, Inceptisols and Alfisols and reported about 26.4 per cent, 20.0 per cent and 8.3 per cent deficiency in available S, respectively (Das *et al.* 2009; Basumatary *et al.* 2010 ; Das *et al.* 2011). S deficiency in Assam have been attributed to continuous use of high analysis S-free fertilizers, inclusion of high yielding varieties used in the intensive cropping system and restricted use of organic manures. Soils under high annual rainfall (>2000 mm) in Assam enhances leaching of SO_4, leaving these soils deficient in S (Borkotoki and Das 2008). Because of the above factors, the areas earlier described as sufficient in available S have started showing S deficiency in some districts of Assam. Thus, to know the exact S supplying capacity of a soil, this present study was undertaken to know different forms of sulphur in relation to soil properties in North blank plain zones of Assam.

Material and Methods

The present investigation was confined to Inceptisols of North Bank Plain Zones (NBPZ) of Assam covering three districts *viz.* Darrang, Lakhimpur and Sonitpur. Seventy five composite surface soil samples (0-15 cm) were collected from different locations of Darrang, Lakhimpur and Sonitpur districts representing major rapeseed-growing areas. The soil map released by NBSS & LUP, Regional Centre, Jorhat (1999) was used as guide map during collection of samples. The processed soil samples (<2 mm) were analyzed for various physico-chemical properties by adopting standard procedures. The soil samples were analyzed for different forms of S *viz.*, total S (Chapman and Pratt 1961), organic S (Evans and Rost 1945), water soluble S (Spencer and Freney 1960), heat soluble S and sulphate S (Williams and Steinbergs 1959) and adsorbed S was calculated by deducting SO_4 - S from the values obtained [illegible] $(H_2PO_4)_2$ extractant (Fox *et al* 1964). Sulphur in all extracts was determined turbidimetrically (Chesnin and Yien 1951). Sulphur Availability Index (SAI) was calculated by the formula outlined by Donahue *et al.* (1977) as :

SAI = (0.4 x $CaCl_2$ extractable SO_4 in mg kg^{-1} soil) + % organic matter

Simple correlation and step-wise multiple regression equations were worked out relating different S fractions with some physico-chemical properties of the soils by standard statistical methods (Gomez and Gomez 1984).

Results and Discussion

The salient physico-chemical properties of soils is presented in table 1.

Forms of Sulphur

Total S

The total S content, which indicates the reserve pool of this element in soil, ranged from 229.45 to 625.50 mg kg^{-1} with mean value of 545.69 mg kg^{-1} (Table 2). The soils of Sonitpur district had highest content of total S (463.39 mg kg^{-1}) might be attributed to the higher amount of organic carbon and clay while lowest was observed in soils of Darrang district (439.96 mg kg^{-1}). Total S exhibited a significant positive correlation with organic carbon (r = 0.795**), clay (r = 0.687**), silt (r = 0.418**), available N (r = 0.488**), available K_2O (r = 0.313**) and negative with pH (r = -0.686**) and sand (r = -0632**) (Table 3). It is established that fine textured soils controls total S along with organic carbon. These relationships corroborates with the finding of Kour and Jalali (2008). Total S was found to be significantly and positively correlated with all forms of S (Table 4). Thus, it indicates that all forms of S maintained a dynamic equilibrium in these soils. Existence of similar relationship among various fractions of S was also reported by Basumatary *et al.* (2008).

The organic carbon content was found to be the dominant soil property which alone explains the maximum variation (63.23%) in total S in soil (Table 7). Inclusion of clay and pH as another variable improved the prediction values by 6.89%. The simultaneous effect of soil properties accounted for

Table 1. Physico-chemical properties of soils

District	Sand (%)	Silt (%)	Clay (%)	Texture	pH	OC (%)	CEC {c mol (p+)kg^{-1}}	N (kg ha^{-1})	P_2O_5 (kg ha^{-1})	K_2O (kg ha^{-1})
Sonitpur	14.4-51.3	16.0-32.0	27.8-56.4	cl-c	4.1-5.9	0.52-0.95	6.00-8.50 (7.21)	175.00-475.95	4.68-14.56	161.28-242.25
	(34.1)	(24.3)	(41.6)			(0.73)		(337.88)	(6.77)	(206.46)
Darrang	28.0-52.0	17.5-32.0	27.5-45.0	cl-c	4.9-6.1	0.55-0.75	8.15-12.85	201.00-395.00	8.66-24.25	109.00-272.40
	(37.4)	(23.6)	(38.0)			(0.65)	(10.45)	(287.36)	(14.96)	(156.41)
Lakhimpur	14.5-59.5	13.5-45.0	27.5-43.5	cl-c	4.0-6.2	0.50-0.87	5.50-9.15 (6.68)	172.00-382.00	5.80-10.80	112.00-282.00
	(31.6)	(29.9)	(36.9)			(0.68)		(241.76)	(7.52)	(181.70)
Mean	25.8	29.2	44.2	-		1.20	10.85	272.37	11.92	292.12

Figures in parenthesis indicate mean values

72.73% variation in total S content of these soils. Similar relationships were also reported by Jat and Yadav (2006).

Organic S

The organic S was found to be the dominant fraction in soils and accounted for 75.20-91.45 per cent of total S in these soil samples (Table 2). The soils of Sonitpur district recorded the highest amount of organic S with mean value of 384.33 mg kg^{-1} followed by Darrang (382.96 mg kg^{-1}) and Lakhimpur district (381.66 mg kg^{-1}). Such variation was due to accumulation of soil organic matter and soil texture (Basumatary *et al.* 2010). These observations were substantiated by the significant positive correlation of organic S with organic carbon and clay. These observations corroborate the finding of Das *et al.* (2011). Correlation studies (Table 3) indicated positive and significant correlation of organic S with clay(r = 0.610**), organic carbon (r = 0.683**), CEC (r = 0.349**) and available N (r = 0.496**) but negatively with sand (r = -0.339**) and pH (r = -0.396**). The multiple regression equations revealed that 56.32 % variation in organic S was attributable to the collective effect of soil properties. Organic carbon alone accounted for about 37.25% variation in organic S. The organic S fraction had positive and significant interrelationship with all other forms of S. This observation is in close agreement with that of Borkotoki and Das (2008).

Table 2. Different forms of S (mg kg^{-1}) in Inceptisols of different districts of Assam

District	Total-S		Organic-S		Water soluble-S		Heat soluble-S		Sulphate-S (SO_4-S)		Adsorbed-S		Sulphur availability indices (SAI)	
	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean
Sonitpur	229.45-625.50	463.39	265.15-512.00	384.33	5.75-27.50	17.77	15.50-40.00	27.98	14.50-32.25	21.70	5.00-15.50	11.70	5.62-15.56	16.26
Darrang	300.00-512.70	439.96	262.25-457.45	382.96	5.15-25.15	13.35	15.80-28.50	20.91	7.50-28.18	15.00	4.50-14.50	7.71	5.5-16.09	15.13
Laklhimpur	300.00-575.50	445.93	266.50-469.80	381.66	4.50-26.25	15.41	15.25-38.75	22.79	7.50-29.37	17.37	4.40-17.30	8.59	8.79-22.34	10.79
Mean		545.69		382.91		127.51		13.63		32.19				13.78

Table 3. Correlation amongst various S-fractions and soil properties

Soil properties	Total-S	Organic -S	Water soluble-S	Heat soluble-SO_4	Sulphate-S (SO_4-S)	Adsorbed-S	Sulphur Availability Indices (SAI)
Sand (%)	-0.632**	-0.339**	-0.653**	-0.547**	-0.592**	-0.560**	-0.603**
Silt (%)	0.418**	0.088	0.455**	0.289*	0.354**	0.326**	0.350**
Clay (%)	0.687**	0.610**	0.625**	0.634**	0.664**	0.622**	0.672**
pH	-0.686**	-0.396**	-0.730**	-0.642**	-0.646**	-0.548**	-0.659**
OC (%)	0.795**	0683**	0.816**	0.826*	0.769**	0.738**	0.796**
CEC {cmol (p+)kg^{-1}}	0.170	0.349**	0.084	0.012	0.035	0.030	0.040
N (kg ha^{-1})	0.488**	0.496**	0.504**	0.615**	0.552**	0.625**	0.560**
P_2O_5 (kg ha^{-1})	-0.189	0.076	-0.330**	-0.327**	-0.386**	-0.414**	-0.385**
K_2O (kg ha^{-1})	0.313**	0.071	0.371**	0.497**	0.538**	0.507**	0.541**

**Significant at 5% level; **Significant at 1% level*

Table 4. Correlation amongst different S-fractions

	Org.-SS	WSS	HSS	SO_4-S	Ad-S	Non-SO_4 - S	Org.-S	TS	SAI
TS	0.840**	0.755**	0.696**	0.651**	0.595**	0.914**	0.278**	0.689**	0.670**
Org.-S		0.462**	0.469**	0.374**	0.365**	0.973**	0.180	0.628**	0.391**
WSS			0.762**	0.827**	0.731**	0.636**	0.303*	0.542**	0.838**
HSS				0.726**	0.753**	0.744**	0.166	0.530**	0.744**
Sul-S					0.803**	0.798**	0.292*	0.682**	0.999**
Ad-S							0.245	0.692*	0.810**

**Significant at 5% level; **Significant at 1% level*

Table 5. Available sulphur status of the soils

District	SAI			AS%		
	Low	Medium	High	Low	Medium	High
Sonitpur (25)	0	44	56	0	44	56
Darrang (25)	44	40	16	40	44	16
Lakhimpur (25)	28	44	28	28	48	24

Figures in the parentheses indicate number of soil sample

Table 6. Average per cent contribution of different S fraction to total S in soils

District	WSS	HSS	SO_4-S	Org-S	Ad-S
Sonitpur	3.70	6.12	4.73	83.12	2.55
Darrang	2.96	4.78	3.36	87.17	1.73
Lakhimpur	3.38	5.12	3.79	85.78	1.90
Grand mean	3.35	5.30	2.70	85.32	2.00

WSS =water soluble S, HSS= heat soluble S, Org S=organic S, Ad S=Adsorbed S

Water soluble S

Water soluble S accounts for a small fraction of total S and on average, soils of Sonitpur, Darrang and Lakhimpur district contributed 3.70, 2.96 and 3.38 per cent to total S, respectively (Table 6). Relatively low concentration of this form might be attributed to leaching loss of sulphate from soil layers. Water soluble S had a strong correlation with all the forms of S. Similar observations have also been reported by Borkokoti and Das (2008) in some Inceptisols of Assam.

Water soluble-S had significant and positive correlation with clay (r = 0.625**), silt (r = 0.455**) and organic carbon (r = 0.816**) indicating the influence of organic matter and finer fractions on sulphur availability. On the other hand, water soluble S exhibited a significant negative correlation with pH (r = -0.730**) and P_2O_5 (r = -0.330**) because when pH increases, sorption of sulphur and phosphorus decreases which in turn augment the water soluble S in soil solution. The regression analysis showed that organic carbon alone contributed 66.52% variation in water soluble S while inclusion of pH and sand improved the contribution level to 72.56%. Soil properties jointly accounted for 73.72% variation in water soluble S.

Heat soluble S

This form of S also referred to as mineralizable S constituted about 6.12, 4.78 and 5.12 per cent of the total S in Sonitpur, Darrang and Lakhimpur district, respectively. Their contents were comparatively larger than water soluble S, sulphate S and adsorbed S (Table 2). Higher amount of heat soluble S might be attributed to release of additional amount of S from organic as well as clay particles on wet and dry heating of soil during extraction. Heating of soil may liberate greater amount of SO_4^{2-} S covalently bonded to organic matter (Aderichin 1960).

Table 7. Effect of soil properties on predictability of different forms of sulphur

Regression equation	R^2
Y_1 (Total-S)= 64.519 +558.539OC	0.632**
Y_1 (Total-S)= 11.126 + 423.526 OC +3.771clay	0.685**
Y_1 (Total-S)= 201.708 + 354.365 OC +3.170clay-23.650pH	0.701**
Y_1 (Total-S)= 188.153+350.859OC+3.039clay-24.342pH- 15.201sand	0.708**
Y_1 (Total-S)= -309.794+438.534 OC+6.039clay-8.075pH +3.914 sand-0.009Av N+2.002silt-0.118 Av K +0.026 Av P+2.826CEC	0.727**
Y_2 (Organic-S)= 91.552+339.652OC	0.373**
Y_2 (Organic-S)= 31.550 + 256.244 OC +6.528 clay	0.447**
Y_2 (Organic-S)= -4.103 + 151.740 OC +4.778 clay+6.084Av N	0.481**
Y_2 (Organic-S)= -180.642 + 201.593OC +6.634 clay +5.995 Av N+10.753 pH	0.520**
Y_2 (Organic-S)= -648.539 + 285.476 OC +9.145clay +0.108 Av N+9.791pH + 6.832 CEC + 6.308 sand +5.273 silt+0.858 P – 0.228 Av K	0.563**
Y_7 (Water Soluble-S)= -19.775+51.154OC	0.665**
Y_7 (Water Soluble-S)= 7.912+37.362OC-3.597pH	0.717**
Y_7 (Water Soluble-S)= 8.499 +35.281 OC-2.799 pH- 0.093 sand	0.726**
Y_7 (Water Soluble-S)= 8.777+34.901 OC-2.656 pH-0.090 sand+2.059clay	0.729**
Y_7 (Water Soluble-S)= - 1.858 +36.240OC -2.249 pH-0.002 sand+0.071 clay+0.093 Av N+0.095 silt -0.014 K– 0.198P + 0.239CEC	0.737**
Y_3 (Heat Soluble-S)= -10.718 +50.186 OC	0.683**
Y_3 (Heat Soluble-S)= -11.476 + 42.533 OC-3.267 pH	0.719**
Y_3 (Heat Soluble-S)= -8.707 + 41.901OC -2.455 pH + 1.115 clay	0.735**
Y_3 (Heat Soluble-S)= -9.585 + 38.517 OC-1.455pH + 0.115 clay + 0.024 Av N	0.747**
Y_3 (Heat Soluble-S)= -9.828 + 32.504 OC -0.875pH +0.180clay + 0.020 Av N + 0.044 sand +0.025 K +0.010 P +0.008 silt-0.530 CEC	0.761**
Y_4 (Sulphate-SO^4) = -14.177+ 46.693OC	0.591**
Y_4 (Sulphate-SO^4) = -18.635 + 6.055 Av K35.418OC + 0.315clay	0.640**
Y_4 (Sulphate-SO^4) = -21.179 +25.459OC K + 0.373 clay – 1.589 pH	0.697**
Y_4 (Sulphate-SO^4) = -18.521 + 25.429 OC + 0.362 clay – 1.120 pH-0.010 sand	0.703**
Y_4 (Sulphate-SO^4) = -24.847 + 23.122 OC + 0.395 clay – 0.556 pH +0.118 sand + 0.010 Av N + 0.033K – 0.077P+0.135 silt-0.147CEC	0.714**
Y_6 (Adsorbed-S)= -7.037 + 23.731 OC	0.545**
Y_6 (Adsorbed-S)= -7.588 + 18.165 OC + 0.015 Av N	0.613**
Y_6 (Adsorbed-S)= -4.569 + 16.054 OC+ 0.015 Av N + 0.091 clay	0.659**
Y_6 (Adsorbed-S)= -5.755 + 13.791OC + 0.013Av N + 0.086 clay -0.026 sand	0.670**
Y_6 (Adsorbed-S)= -28.373 +14.631OC + 0.015 Av N + 0.200 clay +0.108 sand + 1.334pH + 0.011 K -0.114 P+0.181silt-0.065CEC	0.703**
Y_8 (SAI)= -5.673 + 20.404 OC	0.545**
Y_8 (SAI)= -7.455 + 15.896 OC +0.126 clay	0.613 **
Y_8 (SAI)= -8.473 + 11.909 OC + 0.149 clay – 3.058 pH	0.659**
Y_8 (SAI)= -7.412 + 11.897 OC + 0.023 145 clay -2.958 pH-0.172 sand	0.670**
Y_8 (SAI)=-9.951 + 10.975 OC +0.158 clay -0.223pH+ 0.047sand + 0.004 Av N +0.013 K – 0.031 P+ 0.054 silt – 0.059CEC	0.703**

A significant positive correlation between heat soluble S and almost all the soil properties (Table 3) revealed that heat soluble S had direct bearing with these properties. On the other hand, the observed significant and positive correlation of heat soluble S with all forms of S, indicated that almost all forms of S had contributed towards heat soluble S (Table 4). Similar observations have also been made by Sharma and Jaggi (2001) and Basumatary *et al.* (2008). The organic-C content of soil exclusively contributed 68.30% variation in heat soluble-S while soil properties jointly contributed 76.13% variation (Table 7).

Adsorbed S

This fraction accounted for the smallest fraction of the total S ranging from 4.40 to 17.30 mg kg^{-1} (Table 6). Low adsorbed S indicated that due to high rainfall, OH^- ions in rainwater displace adsorbed SO_4^{2-} resulting in its leaching losses. Adsorbed S was highest in soils of Sonitpur district. This higher value might be attributed to the higher amount of organic carbon and clay and thus enhanced the physical adsorption of SO_4^{2-} . Since adsorbed sulphate is considered as the potential source of available S in soil, it is remarkable to observe a significant positive correlation of adsorbed sulphate with organic carbon (r = 0.738**), clay (r = 0.622**) and silt (r = 0.326**) and thereby, indicated their dominant role in sulphate sorption in these soils. Adsorbed S was negatively correlated with pH (Table 3). It has been explained that solution pH virtually controls the polarity and surface charge density of sorption plan like clay and Fe and Al oxides in such a way that the magnitude increases with drop in pH and hence sulphate adsorption increases with decrease in pH. The multiple regression equations revealed that 70.32 % variation in organic S was attributable to the collective effect of soil properties. Organic carbon alone accounted for about 54.48% variation in organic S. It showed significant and positive correlation with other forms of S (Table 4).

Sulphate S

The sulphate fraction of S is the most important for plant nutrient point of view and may prove a suitable index in evaluating the amount of S available to plants. The average SO_4^{2-} ranged from lowest value (15.00 mg kg^{-1}) in Darrang to the highest (21.70 mg kg^{-1}) in Sonitpur soils. This form of S contributed about 4.73, 3.36 and 3.79% in Sonitpur, Darrang and Lahkimpur, respectively (Table 6). Sulphate S was significantly and positively correlated with silt (r = 0.354**), clay (r = 0.664**), organic carbon (r = 0.769**), available N (r = 0.552**) and K (r = 0.538**) while negatively with sand (r = -0.592**), pH (r = -0.646**) and available P (r = -0.386**) (Table 3). Similar observations were also reported by Basumatary (2008). Sulphate S was existed in a state of dynamic equilibrium which was evident from significant positive correlations with all forms of S (Table 4).The step-wise regression equations revealed that 71.39 per cent variation in sulphate S was attributable to the collective effect of soil properties. Organic carbon alone accounted for about 59.11per cent variation in sulphate S.

Delineation of Sulphur Deficient Areas

The Sulphur Availability Index (SAI) was used to delineate the sulphur deficient areas correlating with various soil properties and sulphur forms with step-wise multiple regression analysis. According to this, about 22.70% were found to be deficient, 45.30% under medium and 32.00% under sufficient category (Table 5). Maximum deficiency (44.0%) was observed in Darrang district. The Sulphur Availability Index (SAI) values varied from 5.50-22.34 with mean of 13.78. Correlation study showed that organic-C was the most dominant factor in SAI (r = 0.796**) followed by clay (r = 0.672**). SAI was also significantly influenced by silt, available N and K_2O (Table 3). The multiple regression equations (Table 7) revealed that organic-C alone contributed 54.48% variation in SAI. Inclusion of pH and clay improved the predictability to 65.9%. Soil properties jointly accounted for 70.32% variation in SAI.

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