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Distribution and Availability of Sulphur in some *Terai* Soils under Subtropical Zone of Eastern India

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Abstract

A study was conducted in some *terai* soils under subtropical zone of Eastern India considering some soil series and some benchmark sites to evaluate distribution of available sulphur status and important soil attributes on sulphur availability. The total S content was found to vary widely from 191.18 to 530.40 mg kg^{-1} with an average of 309.21 mg kg^{-1}. The percentage contribution of organic S, sulphate S, adsorbed S, heat soluble S and water soluble S varied from 29.62 to 85.02, 7.85 to 9.94, 0.23 to 9.82, 5.97 to 17.59 and 1.77 to 6.80 per cent to total sulphur in soil samples. Available S was significantly and positively correlated to organic carbon, total N, clay and silt+clay, oxalate-Fe, CBD-Fe and only negative correlated with pH (r = -0.02). Organic S exhibited significant and positive correlations with sulphate, water soluble S, heat soluble S and adsorbed S and played major role in sulphur availability. Significantly positive correlations of sulphate S with water soluble (r = 0.80**), heat soluble (r = 0.70**) and adsorbed S (r = 0.46**) and organic form of S (r = 70**) were found. A significantly positive correlation was observed between water soluble and heat soluble S. Among the soil properties, organic carbon, total N, silt+ clay, CBD-extractable Al and Fe influenced mostly on variability of available S in these soils.

Highlights

- Total sulphur content widely varied and organic fraction mostly dominates in *terai* soils.
- Organic C, N, silt+ clay, CBD-Al and Fe influenced mostly on sulphur availability.

Keywords: Sulphur availability, sulphur distribution, soil physicochemical characteristics

Sulphur is an important part of organic matter and its availability is dependent on its transformation into inorganic forms. It is one of the 17 mineral nutrients which are essential for the growth and development of all plants. Sulphur is also essential for human and animals and is increasingly being recognized as the fourth major plant nutrient after nitrogen, phosphorus and potassium. Available sulphur consisting largely of easily extractable sulphate sulphur is the immediate supplier of sulphate ions to the root of plants. Although organic sulphur is considered to be an important donor of available sulphur, there are several instances where soils with having 300 mg kg^{-1} or more organic sulphur, contained only traces of available ($CaCl_2$-extractable) sulphur. Other than crop uptake, plant available sulphur is subjected to immobilization and leaching as well. In spite of the fact that plants absorb sulphur almost exclusively as sulphate, determination of the sulphate content of a soil is of little use as a measure of sulphate availability. Total sulphur measurement similarly has proved to be of limited usefulness in

Table 1. Physico-chemical properties (mean value) of experimental soils

Soil No.	Soil Series/ Benchmark Site	pH (1:2.5)	OC (%)	Total N (%)	CEC [cmol(+) kg^{-1}]	Clay (%)	Silt+Clay (%) Al	Oxalate extract (%)		CBD-extract (%)		CBD-Al+Fe (%)
								Fe	Al	Fe		
		X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	X_{11}
CoochBehar district												
1	Lotafela	5.56	0.86	0.12	7.64	17.27	36.27	0.12	0.14	0.19	0.20	0.39
2	Balorampur	5.21	1.14	0.15	7.52	17.30	40.63	0.07	0.08	0.06	0.11	0.16
3	Rajpur	4.93	0.81	0.09	6.83	14.50	34.10	0.20	0.22	0.27	0.35	0.62
4	Pundibari	5.92	1.03	0.16	7.42	14.56	38.46	0.08	0.11	0.08	0.14	0.22
5	Matiarkuthi	4.88	0.77	0.12	7.33	13.92	30.23	0.16	0.19	0.27	0.22	0.49
	Jalpaiguri district											
6	Berubari	4.83	1.71	0.19	8.06	14.84	34.34	0.31	0.28	0.40	0.44	0.84
7	Binnaguri	4.50	1.99	0.19	7.82	13.99	33.69	0.34	0.40	0.60	0.60	1.20
8	Moinaguri	5.26	1.23	0.17	7.55	15.76	36.86	0.09	0.15	0.12	0.20	0.32
9	Dhupguri	5.68	1.02	0.16	8.60	17.07	39.97	0.07	0.12	0.07	0.20	0.27
Darjeeling district												
10	Kharibari	5.71	1.10	0.14	7.47	14.54	35.34	0.11	0.22	0.20	0.36	0.56
North Dinajpur district												
11	Islampur	5.55	0.81	0.13	6.95	16.02	39.52	0.08	0.13	0.08	0.18	0.25
Range		4.16-6.50	0.40-2.42	0.06-0.26	3.65-12.58	10.60-23.96	22.72-52.72	0.01-0.81	0.02-0.76	0.02-1.16	0.04-0.81	0.06-2.13
Mean		5.28	1.13	0.15	7.56	15.43	36.31	0.15	0.18	0.21	0.27	0.48

assessing the sulphur availability in soils. Keeping these views, attempts were made to evaluate the available sulphur status and different important soil physico-chemical characteristics to elucidate the influences of these attributes on the availability of sulphur.

Materials and Methods

One hundred and ten (110) representative surface (0–15 cm) soil samples from typical rice and mustard growing fields spread all over the areas representing some *terai* soil under subtropical zone of Eastern India were collected for this study. The processed soil samples were analysed for physicochemical properties like pH, organic carbon, CEC, total nitrogen by standard methods. Clay and silt (Day 1965), Citrate bicarbonate Dithionite - extractable Al and Fe and ammonium oxalate extractable Al and Fe (Page *et al.* 1982) were determined. Available S was extracted by using 0.15% $CaCl_2$ (Williams and Steinbergs 1959). Total S, organic S, adsorbed S, heat soluble S and water soluble S were extracted by using the methods of Tabatabai (1982), Fox *et al.* (1964), Fox *et al.* (1964), Williams and Steinbergs (1959) and Spencer and Freney (1960), respectively. The mean value of each parameter and the correlation coefficients between available sulphur and different soil characteristics were calculated as per procedure referred in Gomez and Gomez (1983). Stepwise regression equations were established by Karl Pearson method as described in Gomez and Gomez (1983).

Table 2. Distribution of available sulphur (mg kg^{-1}) in soils according to locations from where samples were collected

Sl. No.	Soil series/ benchmark sites	Number of samples in each site	Available S (mg kg^{-1}) content		Percent soil samples following in the category		
			Range	Mean	Low (<10 mg kg^{-1})	Medium (10-20 mg kg^{-1})	High (>20 mg kg^{-1})
Coochbehar district							
1	Lotafela	10	16.62-26.77	21.66	0	40.0 (4)*	60.0 (6)
2	Balorampur	10	17.29-36.50	21.88	0	60.0 (6)	40.0 (4)
3	Rajpur	10	15.35-22.96	19.52	0	60.0 (6)	40.0 (4)
4	Pundibari	10	18.75-30.37	23.83	0	10.0 (1)	90.0 (9)
5	Matiarkuthi	10	17.16-27.87	22.39	0	20.0 (2)	80.0 (8)
Jalpaiguri district							
6	Berubari	10	21.46-31.43	25.54	0	0	100 (10)
7	Binnaguri	10	19.41-39.21	28.90	0	10.0 (1)	90.0 (9)
8	Mainaguri	10	16.61-30.16	23.70	0	20.0 (2)	80.0 (8)
9	Dhupguri	10	16.64-30.62	23.45	0	30.0 (3)	70.0 (7)
Darjeeling district							
10	Kharibari	10	18.28-43.26	30.65	0	10.0 (1)	90.0 (9)
North Dinajpur district							
11	Islampur	10	17.26-37.32	23.98	0	20.0 (2)	80.0 (8)
Overall figure		110	15.35 – 43.26	24.14	0	25.46 (28)	74.55 (82)

*figures in the parentheses represent the number of samples in each category of sulphur status in respective cases.

Results and Discussion

Physico-chemical characteristics of soil

The results of some of the important physicochemical characteristics of soils studied are presented in Table 1. A perusal of the data showed that soils varied widely in their pH values ranging between 4.16 and 6.50 with a mean value of 5.28. The organic carbon content of soils also varied widely ranging from 0.40 to 2.42 with an average of 1.13 per cent. CEC of all the samples studied and recorded their values in between 3.65 to 12.58 with a mean of 7.56 cmol(p^+)kg^{-1} soil. In respect of texture, soils showed marked variation in their clay content ranging from 10.60 to 23.96 with having a mean of 15.43 per cent, indicating that soils, in general, are coarse in texture. Similar was the result in respect of combined estimation of silt+clay which accounted for 22.72 to 52.72 with average value of 36.31 per cent. The acid ammonium oxalate extractable Al (ox-Al) and Fe (ox-Fe) fractions, observed to maintain high variability in soils which ranged from 0.01 to 0.81 and 0.02 to 0.76 with mean of 0.15 and 0.18 per cent respectively. The dithionite extractable Al (CBD-Al) and Fe (CBD-Fe) fractions also recorded to have high extent of variability in their contents within the limits of 0.02 to 1.16 and 0.04 to 0.81 with respective means of 0.21 and 0.27 per cent. Combined value of CBD-Al and CBD-Fe also has shown to vary widely between 0.06 and 2.13 with its mean of 0.48 per cent.

Available sulphur

The available S of experimental soils registered a high variation in its content ranging from 15.35 to

Table 3. Correlations (r–values) between some important physicochemical characteristics and available sulphur content of soils

Soil characters	Available sulphur
pH	-0.02
OC	0.34**
Total N	0.27**
CEC	0.04
Clay	0.19*
Silt + Clay	0.24*
Oxalate-Al	0.10
Oxalate-Fe	0.19*
CBD-Al	0.10
CBD-Fe	0.24*
CBD (Al+Fe)	0.18

* and ** : refer to level of significance at 0.05 and 0.01 probability level respectively.

43.26 with an overall mean value of 24.14 mg kg^{-1} soil (Table 2). However, about 25 per cent of total soils under study recorded to have available S status under medium category and almost 75 per cent under high category. However, nearly 11 per cent of total soil samples found to contain available sulphur just on the border line of medium to high category.

Available S status was noticed (Table 2) high, about 60 per cent of total samples from each of Balorampur and Rajpur soil series under CoochBehar district followed by nearly 40 per cent from Lotafela series under CoochBehar. 30 per cent from Dhupguri benchmark site under Jalpaiguri district were observed to contain available S within the medium range, while remaining samples showed high in available S status. However, 10 to 20 per cent of the total samples under medium S availability status along with rest portions into high range were noted for soils collected from other locations. The observed variations of sulphur availability in soils of different series and some identified locations (benchmark site) tested might be due to the presence of variable proportions of different components of organic matter (Basumatary *et al.* 2010), soil and crop management practices such as intensity and nature of crop grown, water use and addition of fertilizers (Patel and Patel 2008; Patel *et al.* 2011).

Relationship of available sulphur with important soil physicochemical characteristics

The values of correlation co-efficient presented in the Table 3, indicated a significant and positive correlation between available sulphur and organic carbon (r = 0.34**) and it was followed by total N (r = 0.27**) content in soils. Soil texture in terms of estimates of clay (r = 0.19*) and silt+clay (r = 0.24*) also showed significant and positive correlations with available S. Since both S and N are the integral constituents of proteins in the organic matter, these two elements use to maintain a definite N:S ratio in the organic matter. Hence, significant and positive relationship of available S with total N and organic carbon content were imminent (Sharma and Jaggi 2001). Similarly texture as one of the major soil characteristics has decided influence on S status in soils as the amount of clay and silt determines the number of edge adsorption sites for sulphur.

Available S extracted by 0.15% $CaCl_2$ reagent that exhibited good positive correlations with oxalate- as well as CBD- extractable Fe and Al forms and combination of CBD (Al+Fe), but it was significant only with Fe fractions (Oxalate-Fe: r = 0.19*; CBD-Fe: 0.24*). It may be attributed to more retention of SO_4^{-2} ions with increase in the amount of amorphous and crystalline Fe and Al fractions which was favoured under acidic soil environment. This was further confirmed in the present study from the negative relationship obtained between the soil pH (r = -0.02) and native SO_4-S content (Basumatary and Das 2012).

Different forms of sulphur in soil

Total sulphur

The total S content was found to vary widely from 191.18 to 530.40 mg kg^{-1} with an average of 309.21 mg kg^{-1} (Table 4). The lowest amount of total sulphur was recorded in the soil sample collected from Balorampur series, while the highest was observed in the sample from Binnaguri series. Most of the soil

Table 4. Different forms of sulphur (mg kg^{-1}) in soils classified according to locations

Soil series/ benchmark sites	No. of sample	Total S		Organic S		Sulphate S		Adsorbed S		Heat soluble S		Water Soluble S	
		Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean
Cooch Behar district													
Lotafela	10	217.14-456.31	312.55	157.09-423.93	279.10	16.62-26.77	21.66	3.43-44.49	16.49	32.15-71.64	44.37	10.49-23.64	16.96
Balorampur	10	191.18-515.65	316.69	170.71-450.92	281.82	17.29-36.50	21.88	4.01-43.49	18.97	31.64-79.86	43.37	10.48-23.08	15.90
Rajpur	10	195.42-289.67	233.83	167.92-261.08	204.50	15.35-22.96	19.52	2.08-32.21	13.74	31.67-56.58	43.73	10.46-21.56	15.59
Pundibari	10	238.1-394.18	309.84	207.83-346.92	276.28	18.75-30.37	23.83	2.10-26.22	13.40	38.46-61.48	46.97	11.81-28.34	20.16
Matiakuthi	10	198.11-382.8	268.03	177.29-350.32	240.04	17.16-27.22	22.39	1.20-21.11	10.35	34.16-49.56	41.59	9.46-25.76	17.64
Overall		191.18-515.65	288.19	157.09-450.92	256.35	15.35-36.50	21.86	1.20-44.49	14.59	31.64-79.86	44.01	9.46-28.34	17.25
Jalpaiguri district													
Berubari	10	245.63-400.55	312.64	209.86-354.79	273.11	21.46-31.43	25.54	4.78-37.5	18.69	37.76-62.48	48.66	14.59-26.56	20.84
Dhupguri	10	227.17-530.40	372.07	232.18-449.85	318.78	19.41-39.21	28.90	6.31-52.09	32.01	47.86-93.27	65.47	14.37-28.46	21.28
Moinaguri	10	204.24-379.11	322.32	176.3-337.2	285.04	16.61-30.16	23.70	6.27-35.18	17.38	35.62-62.47	47.59	10.67-28.76	19.91
Binnaguri	10	203.94-407.76	292.34	169.27-369.41	255.66	16.64-30.62	23.45	4.24-40.33	18.36	35.76-78.72	48.91	9.4-29.74	18.32
Overall		203.94-530.40	259.88	169.27-449.85	226.52	16.61-39.21	20.32	4.24-52.09	17.29	35.62-93.27	42.13	9.40-29.74	16.07
Darjeeling district													
Kharibari	10	249.91-483.92	364.27	212.84-425.41	319.15	18.28-43.26	30.65	10.62-34.01	20.63	42.82-68.49	54.46	11.28-36.09	24.48
North Dinajpur district													
Islampur	10	197.58-368.98	296.72	179.64-319.93	259.08	17.26-37.32	23.98	2.86-33.02	17.36	34.56-67.48	49.61	13.79-34.17	20.29
Grand	110	191.18-530.40	309.21	157.09-450.92	272.05	15.35-43.26	24.14	1.20-52.09	17.94	31.67-93.27	48.61	9.40-36.09	19.22

Table 5. Relationship of different forms of sulphur with various salient characteristics of soil

Forms of S Parameter	Total S	Organic S	Sulphate S	Adsorbed S	Heat Soluble S	Water Soluble S
pH	0.09	0.13	-0.02	-0.20*	-0.17	0.08
OC	0.44**	0.40**	0.34**	0.40**	0.33**	0.15
Total N	0.50**	0.50**	0.27**	0.26**	0.21*	0.15
CEC	0.21*	0.21*	0.04	0.08	0.03	0.04
Clay	0.36**	0.36**	0.19*	0.14	0.11	0.11
Silt + Clay	0.33**	0.32**	0.24*	0.20*	0.13	0.15
Oxalate-Al	0.05	0.02	0.10	0.21*	0.15	0.01
Oxalate-Fe	0.17	0.17	0.19*	0.04	0.09	0.19*
CBD-Al	0.10	0.08	0.10	0.16	0.16	0.04
CBD-Fe	0.20*	0.18	0.24*	0.12	0.21*	0.23*
CBD-(Al+Fe)	0.16	0.13	0.18	0.15	0.20*	0.14

* and ** : refer to significant level at 0.05 and 0.01 respectively.

Table: 6 Correlations (r-value) amongst different forms of sulphur in experimental soils (n = 110)

Forms of S	Total S	Organic S	Sulphate S	Adsorbed S	Heat soluble S
Total S	-				
Organic S	0.99**	-			
Sulphate S	0.77**	0.70**	-		
Adsorbed S	0.37**	0.24*	0.46**	-	
Heat soluble S	0.50**	0.38**	0.70**	0.82**	-
Water soluble S	0.61**	0.60**	0.80**	-0.03	0.38**

* and **: refer to significance at 0.05 and 0.01 levels respectively.

S is consisted in the organic matter, very low organic carbon (0.40%) content in former as against very high amount (2.42%) in the latter one might have contributed to such spectacular variation in total S content (Jat and Yadav 2006).

Distribution of total S ccording to locations revealed (Table 4) that samples belonged to Rajpur series under Coochbehar district contained total S (195.42 to 289.67) with its mean value of 233.83 mg kg^{-1}, being the lowest amongst the different locations considered in this study. While soil samples from Binnaguri series, in general, recorded to have considerably higher total S (227.17 to 530.40) with its mean of 372.07 mg kg^{-1}, which appeared to be the highest amongst all soil locations studied. All the samples from the plain areas of Darjeeling district shown to contain higher amount of total S and it was followed by those from Jalpaiguri district; whereas samples tested from CoochBehar and North Dinajpur district recorded to follow a similar trend and contained relative less total S as compared to others. The overall variations of mean total sulphur status in surface layer of soils among the districts may be ascribed mainly to the differences in organic matter content as influenced by nature and intensity of cropping, soil and fertilizer management practices followed and water use and drainage system (Patel *et al.* 2011; Isitekhale *et al.* 2013).

Organic sulphur

Organic sulphur was shown to maintain a high variability in the range from 157.07 to 450.92 mg kg^{-1} with an average value of 272.05 mg kg^{-1} soil (Table 4), which accounted for 29.62 to 85.02 per cent of total sulphur of the soil samples with a mean of 88 per cent (Figure 1). It was revealed that samples from Rajpur series of CoochBehar district contained relatively less amount of organic sulphur with a mean of 204.50 mg kg^{-1}, being the lowest among all the locations studied. While soil samples from Kharibari benchmark site in plains of Darjeeling district was shown to be relatively higher in organic sulphur status with mean organic sulphur content of 319.15 mg kg^{-1} soil, being the highest among all the locations. Organic S in soils also found to follow a similar trend to that of total S when its inter-district variations were considered. Organic S formed largest fraction of total S in the soils and had significant positive relationship with total S, organic carbon and clay contents in the soils (Isitekhale *et al.* 2013).

Sulphate sulphur

Sulphate S status is found to vary considerably from 15.35 to 43.36 with an overall mean value of 24.14 mg kg^{-1} soil (Table 4) for 110 samples tested in this study. The percentage contribution of sulphate S to total S also varied from 7.85 to 9.94 per cent with a mean value of 7.8 per cent (Figure 1). Samples from Kharibari benchmark site observed to have relatively higher sulphate S with a mean sulphate S content of 30.65 mg kg^{-1} soil followed by that of Binnaguri series (28.90 mg kg^{-1} soil) under Jalpaiguri district.

Adsorbed sulphur

Adsorbed form of sulphur was found to maintain high variations within the range from 1.20 to 52.09 mg kg^{-1} soil with a mean value of 17.94 mg kg^{-1} soil (Table 4). This form of sulphur comprising the smallest fraction of the total S accounted for 0.23 to 9.82 per cent with a mean of 5.8 per cent of total S (Figure 1). The highest amount of adsorbed S obtained in the particular soil sample belonging under Binnaguri series might have been due to the presence of very high total S, organic S and organic matter content ((Isitekhale *et al.* 2013) along with presence of notably higher Al and Fe oxides (Basumatary and Das, 2012) as compared to those in other locations which collectively contributed to higher retention of sulphate S on adsorptive sites. Adsorbed S status when compared amongst the soil series and benchmark sites, it was observed that majority of soil samples from Binnaguri series of Jalpaiguri district retained very high amounts of sulphate S in adsorbed form as compared to those recorded in any other locations; the mean concentration of which being with 32.01 mg kg^{-1} soil was regarded as the highest value amongst the all locations.

Heat soluble sulphur

This form of S, which indicates the mineralizable S varied (Table 4) in soil samples from 31.67 to 93.27 with a mean value of 48.61 mg kg^{-1}. Soils used in this study shown where higher heat soluble S than water soluble S, sulphate S and adsorbed S, thereby indicating the release of S by wet and dry heating of the soil during the extraction. Higher amount of heat soluble S might be attributed to release of additional amount of S from organic carbon (Ogeh *et al.* 2012) as well as clay particles on wet and dry heating of soil during extraction (Basumatary and Das, 2012) and . Heating of soil may liberate greater amount of SO_4^{-2}- S covalently bonded to organic matter (Aderichin 1960). This form of S constituted 5.97 to 17.59 per cent with a mean value of 15.70 per cent of (Figure 1) total S. The status of heat soluble S in soils when compared amongst the soil series and benchmark sites from where the samples were collected, relatively higher

Table: 7 Soil characteristics/properties predicting S availability using different indices (n = 110)

Regression equation	Cumulative contribution (R^2 x 100)	Contribution of individual soil characters (R^2 x 100)
Total S		
$Y = 181.62 + 865.82X_3$	25	25
$Y = 75.37 + 786.14X_3 + 7.65X_5$	33	8
$Y = 59.27 + 754.99X_3 + 7.98X_5 + 57.22X_{10}$	36	3
$Y = -25.78 + 761.36X_3 + 7.31X_5 + 70.07X_{10} + 17.24X_1$	37	1
$Y = -55.67 + 497.24X_3 + 7.56X_5 + 58.94X_{10} + 23.39X_1 + 31.33X_2$	38	1
Organic S		
$Y = 157.36 + 778.31X_3$	24	24
$Y = 59.53 + 704.95X_3 + 7.04X_5$	33	9
$Y = 40.59 + 679.91X_3 + 7.31X_5 + 45.95X_{10}$	35	2
$Y = -53.33 + 687.42X_3 + 6.52X_5 + 61.06X_{10} + 20.25X_1$	37	2
$Y = -32.19 + 699.77X_3 + 6.31X_5 + 81.19X_{10} + 17.02X_1 - 55.18X_7$	37	Fraction
Sulphate S		
$Y= 19.38+ 4.20X_2$	11.4	11
$Y= 11.66+ 4.12X_2 + 0.22X_6$	17	6
$Y= 10.79+ 3.43X_2 + 0.23X_6 +4.24X_{10}$	19	2
$Y= 11.58+ 3.91X_2 + 0.20X_6 + 8.46X_{10} - 6.06X_9$	21	2
$Y= 13.63+ 4.44X_2 + 0.21X_6 + 8.38X_{10} - 6.45X_9 -0.39X_3$	22	1
$Y= 13.78+ 4.33X_2 + 0.20X_6 - 404.89X_{10} - 419.62X_9 -0.37X_3 - 413.18X_{11}$	23	1
Adsorbed S		
$Y = 6.58 + 10.03X_2$	16	16
$Y = -6.65 + 9.89X_2 + 0.37X_6$	19	3
$Y = -5.17 + 16.55X_2 + 0.47X_6 - 85.9X_3$	22	3
$Y = -3.66 + 18.05X_2 + 0.45X_6 - 93.99X_3 - 7.92X_8$	23	1
$Y = -4.48 + 16.25X_2 + 0.45X_6 - 80.18X_3 - 12.30X_8 + 10.66X_7$	24	1
$Y = 6.02 + 14.75X_2 + 0.49X_6 - 68.15X_3 - 12.37X_8 + 8.81X_7 - 2.20X_1$	25	1
Heat soluble S		
$Y = 38.67 + 8.78X_2$	11	11
$Y = 29.57 + 8.69X_2 +0.25X_6$	13	2
$Y = 30.86 + 14.49X_2 +0.34X_6 - 74.84X_3$	15	2
$Y = 33.97 + 14.8X_2 +0.36X_6 - 69.52X_3 - 0.65X_4$	15	Fraction
Water soluble S		
$Y = 17.64 + 5.78X_{10}$	5	5
$Y = 17.67 + 11.93X_{10} - 8.07X_9$	10	5
$Y = 14.75 + 12.13X_{10} - 8.82X_9 + 20.55X_3$	12	2
$Y = 8.09 + 11.97X_{10} - 7.33X_9 - 19.87X_3 + 1.23X_1$	13	1

X_1 = pH	X_2 = OC	X_3 = Total N
X_4 = CEC	X_5 = Clay	X_6 = Silt + Clay
X_7 = OX-Al	X_8 = OX-Fe	X_9 = CBD-Al
X_{10} = CBD-Fe	X_{11} = CBD (Al + Fe)	

content of S in this form in the samples from Binnaguri series alongwith the highest mean of 65.47 mg kg^{-1} was observed.

Water soluble sulphur

Water soluble S content in experimental soils ranged from 9.40 to 36.09 mg kg^{-1} with an overall mean value of 19.22 mg kg^{-1} soil (Table 4) and constituted 1.77 to 6.80 per cent alongwith its average of 6.2 per cent (Figure 1) of the total S and Kharibari sites of Darjeeling district contained relatively higher. Results further showed that water soluble S status in these soils recorded higher value (mean 19.22 mg kg^{-1}) than the adsorbed S (mean 17.94 mg kg^{-1}), but it was lower than sulphate S content (mean 24.14 mg kg^{-1}) in all the samples studied.

The overall low water soluble S status as compared to sulphate sulphur was most likely due to natural leaching of soluble S compounds because of light soil texture and prevalence of high annual rainfall (>2000 mm/annum) areas (Paul *et al.* 2011; Paul and Mukhopadhyay 2014).

Relationship among different forms of S and with important soil properties

Amongst the relationships worked out between different forms of S and soil properties (Table 5), total S content in soils was found to be positively and significantly correlated with total N (r = 0.50**), organic carbon (r = 0.44**), finer soil separates measured in terms of clay (r = 0.36**) and silt+clay (0.33**) indicating thereby the presence of most of the S in these soils in association with organic matter (Paul and Mukhopadhyay 2009) in terai soils of West Bengal. Total S content also recorded positive correlation with CEC (r = 0.21*), free iron oxide (CBD-Fe; r = 0.20*) and amorphous and organically bound Fe (oxalate-Fe), but it was not significant in case of oxalate-extractable-Fe compounds.

Correlation studies (Table 5) revealed that organic form of S in these soils exhibited similar relationships to that of total S in respect of the properties *viz.* total N (r = 0.50**), organic carbon (r = 0.40**), clay (r = 0.36**), silt+clay (r = 0.32**) and CEC (r = 0.21*); but with CBD-Fe, it was not significant.

Sulphate S was significantly and positively correlated with organic carbon (r = 0.34**), Total N (r = 0.27**) clay (r = 0.19*), silt+clay (r = 0.24*), oxalate Fe (r = 0.19) CBD-Fe (r = 0.24*) (Table 5). Sulphate S was negatively correlated with the pH (r = -0.02) of the soil.

Adsorbed form of S was found to correlate significantly and positively with organic carbon (r = 0.40**), total N (r = 0.26**), silt+clay (r = 0.20*) and oxalate-Al (r = 0.21*) content of soils, but with CBD-Al correlation value was merely below the level of significance. While a significant but negative correlation between adsorbed S and soil pH (r = -0.20*) was observed which clearly indicated that increase in soil pH would result into decrease in the amount of S in this form, attributing it to the reduced adsorption of sulphate in soils and its consequent losses through leaching (Basumatary and Das, 2012).

Heat soluble S followed almost a similar trend to that of adsorbed form of S in respect of its relationship with soil properties. It recorded significant positive correlations with organic carbon (r = 0.33**) and total N (r = 0.21*) content of soils. Significant positive correlations were also observed with CBD-Fe (r = 0.21*) and CBD-(Al+Fe) combined (r = 0.20*). Whereas a negative correlation between heat soluble S and soil pH with its r-value very close to attain the level of significance was noticed.

Water soluble S was found to correlate positively but non-significant with all the soil properties tested in this study, except with CBD-Fe (r = 0.23*) and oxalate-Fe (r = 0.19*) which showed significant.

Results of correlations (r-values) among different forms of S have presented in the table 6, it was observed that total S had significant positive relationship with all forms of S studied in this experiment. Khalid *et al*. (2011) obtained significant positive relationships between plant available S ($CaCl_2$ extractable $SO4^{-2}$-S) and the total S, organic S and organic C contents in soils of Pakistan. Organic form of S exhibited highly significant and positive correlations with sulphate S (r = 0.70**) and water soluble S (r = 0.61**) but it was also related positively and significantly with heat soluble sulphur (r = 0.38**) and adsorbed form of sulphur (r = 0.24*) with lower magnitude of r-values. Strong positive relationship of sulphate S with water soluble (r = 0.80**), heat soluble (r = 0.70**) and adsorbed form of S (r = 0.46**) indicated that these forms of S remained in a state of dynamic equilibrium (Basumatary and Das, 2012). Adsorbed S was found to maintain a very high significant and positive relation with heat soluble S (r = 0.82**) suggesting that with increase in amount of heat soluble S there was an increase of the adsorbed fraction of S in these soils. Water soluble S showed significant and positive correlation between water soluble and heat soluble S (r = 0.38**) was observed.

Influence of soil properties on variability of different forms of sulphur

Results revealed that total N alone contributed to 25 per cent variation in total S in soils (Table 7). Inclusion of clay as another variable improved the predictability by 33 per cent. These two soil parameters together with CBD-Fe, pH and organic carbon collectively accounted for 38 per cent variation of total S in soils. Organic sulphur also followed a similar pattern to that of total sulphur, wherein above said properties, except with soil pH, conjointly contributed to a maximum 37 per cent of its variation in soils. The collective influence of organic carbon, silt+clay, CBD-Fe, CBD-Al, pH and CBD (Al+Fe) content accounted for only 23 per cent variation in available S in soils. Similarly organic carbon content alone caused 16 per cent variation in adsorbed sulphur as against the collective contribution of 25 per cent by silt+clay, total N, oxalate-Fe, oxalate-Al and soil pH. This indicated that the organic carbon and silt+clay were predominant soil properties in influencing the variability of adsorbed sulphur in these soils. In heat soluble form, organic carbon contributed to only 11 per cent of the variation and inclusion of silt+clay and total N as other two variables resulted to improve the predictability only upto 15 per cent. Free iron oxide (CBD-Fe) and CBD-Al accounted for 10 per cent of variation in water soluble S and inclusion of total N into the equation resulted to improve the prediction value by 12 per cent. However, inclusion of total N and pH contributed to explain only 13 per cent of its variation in soils.

Conclusion

Results obtained in the present investigation, thus, revealed that distribution of different S forms in surface layer of soils is greatly influenced by soil properties and inter-relationships amongst themselves. Organic S in soil constitutes the most predominant fraction and occurs as the major native S reserves in soils. Among the soil properties, organic carbon, total N, silt+ clay, CBD-extractable Al and Fe showed to have major influences on variability of available S in these soils.

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