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Vertical Distribution of Forms of Sulphur in Relation to Physicochemical Properties of Lateritic Soils of Eastern India

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Sulphur (S) deficiency is widespread in Indian soils, and it has been emerging as a major problem in rice-growing lateritic soils of West Bengal. The vertical distribution of S forms and their relationships with soil physicochemical properties were examined in 50 rice-growing locations of lateritic soils of West Bengal, India, for the current study. For this a total of one hundred fifty representative soil samples were collected from three depths and fifty representative locations of rice-based cropping systems of lateritic belt of West Bengal and analyzed for different fractions of S and important physicochemical properties using standard methodology. Most soils were sandy clay loam to clay loam, with low to medium levels of organic carbon, and strongly acidic to moderately acidic. A decrease in organic carbon across the depths was evident. Among the sulphur forms, organic S was dominant, and the contribution of water-soluble S was least throughout the soil

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profile. The studied sulphur forms followed the order: total S > organic S > heat soluble S > adsorbed S > sulphate S > water soluble S. Except for adsorbed S, most forms decreased with soil depth. The correlation study revealed that soil pH was positively and significantly correlated with water soluble (r = 0.431**) and sulphate S (r = 0.325*) in surface soils, with sulphate S both in mid-surface (r = 0.450**) and subsurface soils (r = 0.423**). Organic carbon showed a positive correlation with all the S forms throughout the profile. Both clay and silt content positively affected S forms, while sand content showed a negative relationship. Positive correlation among all the S forms observed along soil depth, except for a negative correlation between adsorbed S and sulphate S. This investigation will be helpful for sulphur management to optimize crop yields in lateritic soils.

Keywords: Sulphur forms; correlation; soil depth; soil properties; lateritic soil.

1. INTRODUCTION

For Indian agriculture, sulphur is currently regarded as one of the most essential nutrients for the growth and development of plants [1,2]. Sulphur, which ranks after nitrogen, phosphorus, and potassium as the fourth most important nutrient for plants, is also crucial for humans and other animals [2]. Sulphur's significance as a secondary plant nutrient is well known and it is essential for the nutrition of cereals, oil seed and pulse crops due to its high requirement [3-6]. Sulphur plays an important role in the formation of chlorophyll and is associated with the formation of biologically important compounds like thiourea, plant regulators, thiamin, biotin and glutathione [7]. In addition to being involved in the metabolic and enzymatic processes of all living cells, it is crucial for the synthesis of proteins and amino acids, especially those containing sulphur [8]. Therefore, maintaining an ideal level of sulphur in the soil is crucial for maximizing crop production and its quality.

Sulphur application had a significant impact on the yield-related characteristics of crops [9]. Aside from nutrient sources, the soil is the primary source of sulphur [10]. A significant factor in determining the amount of sulphur absorbed by crops is the status of other major nutrients, particularly nitrogen and phosphorus and other physicochemical properties of soil [9,11,12]. Therefore, even under excellent management practises and regardless of all other nutrient applications, the absolute yield potential of a crop cannot be obtained in soils that are lacking in S content [9].

Crop production is considered to be globally constrained by sulphur deficiency. There are numerous reports of sulphur deficiencies throughout the world [10]. On average, 41 percent of Indian soils have reported S deficiency [13]. Reports indicated that, S deficiency was widespread in red-lateritic, coarse-textured alluvial, leached acidic hill soils and black clayey soils [14]. It is more pronounced in Alfisols than Vertisols [9]. The results of different investigations indicated that, soils of West Bengal are extensively deficient in sulphur, which is particularly noticeable in coarse-textured lateritic soils and Entisols [15-17]. Use of high analysis fertilizers with less or zero sulphur content, reduced or no use of organic manures, followed by crop uptake with high yielding varieties and adsorption of S in acid soils are the major reasons of sulphur deficiency in crop production [18]. Though the efficiency of sulphur is only 8–10% [19], the severity of this deficiency varies according to these regions' physicochemical characteristics of soil as well as the climatic conditions [15,12,20].

As 90% of the total S is present in organic form, it is preferable to study the various forms of S rather than the available ones to determine a soil's capacity to supply S [21,22]. The availability of sulphur is influenced by a number of soil conditions, and as a result, the status of various forms of sulphur in soils varies greatly with soil type [23,24,31]. Both inorganic and organic forms of sulfur are found in soil. Sulphur exists in soil in different forms, viz, water soluble S, sulphate S, organic S, adsorbed S, heat soluble S and total S. Due to different losses, mainly through leaching, sulphate sulphur only makes up a small portion of total sulphur (1.25 to 17.7%), especially in soils with a coarse texture [25]. The sulphur-supplying capacity of a soil is determined by the types of sulphur and how they interact with soil characteristics to affect the release and its dynamics [22]. As sulphur exists in different forms, the knowledge of these forms of sulphur in soils together with their distribution in the root zone is of much relevance in assessing the sulphur-supplying capacity of the soils [26]. The information on the vertical distribution of different S fractions under rice-based cropping systems is scanty, particularly in the lateritic soils of West Bengal. In view of this, the present study was undertaken to assess the vertical status of different forms of S and identify the relationship between the S forms and physicochemical properties of lateritic soils.

2. MATERIALS AND METHODS

2.1 Sampling and Analyses of Soil

A total of one hundred fifty soil samples were collected following standard soil sampling protocol from fifty representative locations of rice-based cropping systems (where no sulphur was applied) in lateritic zones of West Bengal, India. The investigation covered five different blocks, namely Bolpur, Illambazar, Dubrajpur, Sainthia and Md. Bazar and sampling was done at three different depths: the surface (0–20 cm), mid-surface (20–40 cm), and subsurface (40–60 cm) from each location. Thus, the actual number of representative soil samples that were gathered and processed (air dried, grinded, and sieved) for the analysis was 150 [5 (blocks) X 10 (locations) X 3 (depths) = 150]. The processed samples were analyzed for physicochemical properties, including mechanical analysis, pH, organic carbon (OC) and cationic exchange capacity (CEC). The analysis was carried out in the soil testing laboratory run by the department of soil science and agricultural chemistry at Visva-Bharati University in West Bengal, India, in 2019–20 using the established protocols. The hydrometer method was followed for mechanical analysis, whereas soil pH was evaluated using 1:2.5 soil: water suspension [27]. Soil organic carbon content was determined by the Walkley and Black method [28]. The method outlined by Schollenberger and Simons [29] was used to determine the cation exchange capacity (CEC). Different extraction methods recommended by various scientists were used to evaluate the various fractions of S (Table 1).

3. RESULTS AND DISCUSSION

3.1 Physicochemical Characteristics of Soils

The findings of some important physicochemical properties of the soils studied are presented in Table 2. A careful analysis of the outcomes showed that, sand fraction (%) in the surface (0–20 cm) soils under investigation varied from 21.24 to 76.56 with a mean value of 50.04, whereas the silt fraction (%) varied from 4.72 to 36.16 with a mean value of 17.99. Clay (%) content ranged from 12.72 to 51.60, with an average value of 31.89. On the basis of relative proportion of different soil separates, the textural class of most of the soils studied varied from sandy clay loam to clay loam. With increasing depth, clay content increased while silt and sand content decreased. The average values pH values ranged from 4.12 to 5.61, 5.14 to 6.59, 5.10 to 6.34, 4.54 to 5.88 and 4.22 to 5.59 in surface soils of Bolpur, Illambazar, Dubrajpur, Sainthia and Md. Bazar blocks respectively. The highest pH (6.98) was observed in sample analyzed from the lower layer of the Dubrajpur block, whereas the lowest pH (4.12) observed in the surface soils of the Bolpur block. The majority of the samples analyzed fall into the strongly acidic to moderately acidic category. Similar findings also reported by Kundu [26], Ghosh et al. [17]. The variation in soil pH might be ascribed to the difference in the parent material from which soil developed, vegetation, topography, climatic conditions and management practices [17]. The organic carbon content (%) of surface soils (0–20 cm) varied from 0.32 to 0.67 (0.48 ± 0.11), 0.34 to 0.73 (0.51 ± 0.15), 0.15 to 0.58 (0.38 ± 0.15), 0.44 to 0.73 (0.59 ± 0.11) and 0.52 to 0.76 (0.65 ± 0.09) respectively, in soils from Bolpur, Illambazar, Dubrajpur, Sainthia and Md. Bazar blocks.

From the average values, it can be seen that most of the soils under investigation fall into the low-to-medium category in organic carbon content. A decrease in organic carbon across the depth showed all the blocks under study. Similar findings also reported by Chattopaddhyay and Ghosh [30]. The average CEC of the total examined soils was 9.39 C mol (P^+) kg^{-1}, with a range of 5.40 to 23.32 C mol (P^+) kg^{-1}. The increase in CEC with depth may be due to an increase in the clay content of the soil [30].

3.2 Forms of Sulphur and Its Relationship with Soil Physicochemical Properties

The distribution of different S forms under study area (Tables 3 to 5) and its interaction with important physicochemical properties of the soils (Table 6) are presented here.

Table 1. Extraction methods of different forms of sulphur

Sl. No.	Forms	Condition; Extraction procedure
1	Water soluble sulphur (Ws-S)	Water soluble S extracted by shaking with distilled water as proposed by Freney [51].
2	Organic sulphur (Org-S)	Organic S was determined by digestion with hydrogen peroxide [52] and subsequent extraction with NaCl solution [53]
3	Sulfate sulphur (Sulph-S)	Sulfate S can be extracted with 0.15% calcium chloride ($CaCl_2$) as suggested by Williams and Steinbergs [53].
4	Adsorbed sulphur (Ads-S)	Adsorbed S by extracted with potassium (K) dihydrogen phosphate (500 ppm P) as suggested by Fox et al. [54].
5	Heat Soluble sulphur (Hs-S)	Heat Soluble S extracted from the soil by special heat treatment and with 0.1% NaCl solution as described by Williams and Steinbergs [53]
6	Total sulphur (Tot-S)	Total sulphur content can be determined by diacid digest method (hydrofluoric acid and perchloric acid) as given by Black [55].

Table 2. Physico-chemical characteristics of lateritic soils of Birbhum District, West Bengal

Locations	Sand (%) at depth (cm)			Silt (%) at depth (cm)			Clay (%) at depth (cm)			pH at depth (cm			OC (%) at depth (cm)			CEC [C mol (P+) kg^{-1}] at depth (cm)		
	0–20	**20–40**	**40–60**	**0–20**	**20–40**	**40–60**	**0–20**	**20–40**	**40–60**	**0–20**	**20–40**	**40–60**	**0–20**	**20–40**	**40–60**	**0–20**	**20–40**	**40–60**
Bolpur																		
Range	29.12–76.56	26.40–75.84	24.40–73.84	4.72–30.72	6.72–28.72	6.72–26.72	12.72–48.16	16.16–51.60	18.88–55.60	4.12–5.61	4.35–5.84	5.11–6.15	0.32–0.67	0.22–0.38	0.11–0.24	6.90–19.22	7.82–21.64	10.11–23.32
Mean	57.47	54.83	51.34	14.32	14.18	13.76	28.21	30.99	34.90	4.97	5.27	5.58	0.48	0.29	0.15	11.19	12.64	14.11
SD	18.79	18.61	18.31	8.83	7.87	7.21	11.23	11.74	12.16	0.52	0.46	0.35	0.11	0.06	0.04	4.08	4.25	4.43
Illambazar																		
Range	24.40–68.40	20.40–65.12	19.12–62.40	6.72–26.72	6.00–26.72	4.00–22.72	22.88–51.60	27.60–52.88	31.60–54.88	5.14–6.59	5.71–6.78	6.17–6.94	0.34–0.73	0.21–0.63	0.10–0.29	6.40–13.70	6.90–15.20	7.90–17.80
Mean	50.27	46.80	44.29	17.36	17.10	15.56	32.37	36.10	40.15	5.92	6.26	6.58	0.51	0.39	0.20	10.18	11.01	12.50
SD	17.13	17.38	16.95	8.75	8.92	9.26	10.11	10.11	8.85	0.46	0.38	0.25	0.15	0.14	0.07	2.87	3.20	3.67
Dubrajpur																		
Range	21.24–68.56	22.40–66.40	21.12–62.40	8.00–36.16	6.00–33.28	6.72–34.00	21.44–51.60	26.16–53.60	30.88–54.16	5.10–6.34	5.49–6.74	5.79–6.98	0.15–0.58	0.11–0.39	0.08–0.24	6.20–14.60	8.20–16.80	10.20-19.30
Mean	46.06	44.51	41.55	20.18	18.25	18.52	33.76	37.25	39.93	5.69	6.40	6.64	0.38	0.24	0.14	9.30	11.35	13.49
SD	20.02	17.30	16.70	10.37	8.23	8.81	10.88	10.12	8.79	0.50	0.37	0.34	0.15	0.09	0.05	2.75	2.79	2.80
Sainthia																		
Range	25.68–75.12	23.68–72.40	22.40–68.40	10.72–32.72	10.72–32.00	12.00–30.72	14.16–51.60	16.88–52.88	19.60–59.60	4.54–5.88	5.22–6.41	5.89–6.58	0.44–0.73	0.22–0.47	0.11–0.26	6.20–11.30	8.40–14.50	10.80–14.80
Mean	47.22	44.34	41.76	20.50	20.56	19.76	32.28	35.10	38.48	5.18	5.85	6.51	0.59	0.36	0.18	8.89	10.76	12.84
SD	18.52	17.38	17.21	7.40	7.08	6.75	12.40	11.38	12.69	0.46	0.45	0.35	0.11	0.07	0.06	1.96	2.19	1.43
Md. Bazar																		
Range	26.40–71.68	27.68–69.12	24.40–65.12	2.72–30.00	4.72–28.72	6.00–24.00	25.60–50.88	26.16–52.88	28.16–57.60	4.22–5.59	4.55–6.26	5.12–6.85	0.52–0.76	0.24–0.58	0.12–0.32	5.40–11.5	6.90–13.80	8.60–14.60
Mean	49.18	47.27	44.47	17.98	17.18	16.03	32.84	35.55	39.50	4.87	5.46	5.94	0.65	0.41	0.20	7.42	9.22	10.78
SD	16.82	16.39	16.09	9.82	8.33	7.03	8.38	9.26	10.21	0.44	0.48	0.48	0.09	0.10	0.06	2.05	2.26	2.09

Table 3. Vertical distribution different forms of sulphur (mg kg^{-1}) in soils of Bolpur and Illambazar block of Birbhum District, West Bengal

Sample	Ws-S at depth (cm)			Org-S at depth (cm)			Sulph-S at depth (cm)			Ads-S at depth (cm)			Hs-S at depth (cm)			Tot-S at depth (cm)		
	0–20	20–40	40–60	0–20	20–40	40–60	0–20	20–40	40–60	0–20	20–40	40–60	0–20	20–40	40–60	0–20	20–40	40–60
Bolpur																		
S1	1.89	1.24	0.32	128.34	95.17	32.51	7.55	3.11	2.05	10.12	13.25	14.12	39.31	28.02	19.17	223.17	135.33	73.34
S2	1.56	1.15	0.34	136.17	102.67	65.29	8.68	4.66	3.22	12.75	17.18	23.25	45.20	33.99	20.90	367.14	245.87	130.13
S3	2.32	1.52	0.57	115.38	98.34	28.79	7.95	5.00	3.87	14.80	16.30	21.37	53.87	41.83	25.06	247.92	194.48	80.37
S4	3.09	2.25	1.15	120.09	85.66	54.10	9.38	6.81	4.90	13.08	15.22	23.29	49.06	37.66	28.73	278.24	201.67	145.26
S5	2.15	1.08	0.56	103.47	76.16	33.37	6.95	3.37	1.34	14.79	16.74	20.81	33.43	19.99	10.06	250.07	186.33	83.85
S6	2.66	1.79	0.97	152.39	125.27	75.04	8.57	5.02	2.83	10.06	16.88	21.95	35.75	24.85	15.92	447.32	305.74	128.96
S7	1.57	1.07	0.35	98.11	62.17	22.08	6.42	4.75	1.56	18.25	21.05	23.12	36.20	20.22	11.29	216.6	107.56	75.22
S8	2.48	2.05	1.22	145.81	82.24	35.15	6.86	3.39	1.42	13.88	16.89	23.96	50.48	28.27	13.34	365.13	244.20	139.70
S9	2.01	1.58	0.73	152.95	124.52	72.34	8.69	5.80	1.92	15.51	17.85	24.52	56.45	34.54	21.11	432.43	316.74	185.24
S10	2.37	1.34	0.82	119.25	73.48	36.37	7.84	4.62	2.23	12.54	16.33	19.40	53.04	35.24	14.31	317.28	263.58	154.20
Range	1.56–3.09	1.07–2.25	0.32–1.22	98.11–152.95	62.17–125.27	22.08–75.04	6.42–9.38	3.11–6.81	1.34–4.90	10.06–18.25	13.25–21.05	14.12–24.52	33.43–56.45	19.99–41.83	10.06–28.73	216.60–447.32	107.56–316.74	73.34–185.24
Mean	2.21	1.51	0.70	127.20	92.57	45.50	7.89	4.65	2.53	13.58	16.77	21.58	45.28	30.46	17.99	314.53	220.15	119.63
SD	0.48	0.41	0.33	19.40	20.94	19.42	0.95	1.15	1.17	2.47	1.97	3.05	8.49	7.38	6.08	84.80	68.15	39.01
Illambazar																		
S1	3.20	1.84	0.55	179.82	86.05	48.85	9.40	7.92	6.03	25.03	28.35	29.28	50.95	31.94	21.01	521.51	282.94	120.38
S2	2.65	1.33	0.56	128.01	71.55	42.63	8.12	5.11	3.10	18.77	21.83	23.41	49.84	24.75	14.90	221.05	147.48	102.17
S3	2.22	1.24	0.29	149.98	98.22	37.13	8.06	4.05	2.74	25.37	27.01	28.53	36.68	28.91	18.73	427.15	193.28	124.41
S4	3.10	1.83	0.42	142.37	64.54	39.44	6.99	4.35	2.77	20.65	23.53	25.45	45.51	30.58	19.57	298.23	202.09	104.30
S5	2.04	1.10	0.49	176.16	93.04	56.71	8.72	6.86	5.22	25.04	29.00	32.97	51.84	34.91	22.89	510.98	214.94	134.89
S6	2.48	1.22	0.21	136.68	81.15	42.38	8.72	4.54	2.78	21.43	23.95	26.11	46.70	25.77	14.76	308.83	204.19	106.00
S7	1.81	1.14	0.44	123.55	52.05	27.42	6.02	5.39	4.08	22.59	25.54	26.28	56.07	23.19	11.13	275.08	175.35	117.26
S8	2.95	1.48	0.69	145.25	66.40	36.49	7.83	5.93	4.29	26.96	28.63	30.12	41.12	28.14	17.18	363.19	286.81	170.35
S9	1.45	1.16	0.33	133.69	56.11	25.68	7.28	5.66	4.82	21.82	25.60	28.68	38.39	29.47	16.95	421.34	211.35	138.28
S10	3.11	1.79	0.72	181.39	92.36	53.71	9.61	6.03	3.10	22.11	24.26	26.56	52.09	36.17	23.15	545.04	190.17	129.24
Range	1.45–3.20	1.10–1.84	0.21–0.72	123.55–181.39	52.05–98.22	25.68–56.71	6.02–9.61	4.05–7.92	2.74–6.03	18.77–26.96	21.83–29.00	23.41–32.97	36.68–56.07	23.19–36.17	11.13–23.15	221.05–545.04	147.48–286.81	102.17–170.35
Mean	2.50	1.41	0.47	149.69	76.15	41.05	8.08	5.58	3.89	22.98	25.77	27.74	46.92	29.38	18.03	389.24	210.86	124.72
SD	0.61	0.30	0.17	21.77	16.30	10.17	1.11	1.19	1.18	2.54	2.43	2.73	6.44	4.21	3.83	113.43	43.61	20.39

Table 4. Vertical distribution different forms of sulphur (mg kg^{-1}) in soils of Dubrajpur and Sainthia block of Birbhum District, West Bengal

Sample	Ws-S at depth (cm)			Org-S at depth (cm)			Sulph-S at depth (cm)			Ads-S at depth (cm)			Hs-S at depth (cm)			Tot-S at depth (cm)		
	0–20	**20–40**	**40–60**	**0–20**	**20–40**	**40–60**	**0–20**	**20–40**	**40–60**	**0–20**	**20–40**	**40–60**	**0–20**	**20–40**	**40–60**	**0–20**	**20–40**	**40–60**
Dubrajpur																		
S1	1.87	1.25	0.74	110.08	80.27	26.17	6.22	4.57	2.63	14.46	17.34	20.47	35.47	20.97	16.86	293.83	209.31	134.38
S2	3.02	1.63	1.06	154.18	101.77	78.95	9.35	8.21	4.90	14.80	15.86	21.60	53.91	36.94	25.75	442.09	284.85	172.17
S3	2.34	1.11	0.56	103.99	82.44	47.45	5.25	4.24	2.54	11.20	12.04	16.72	39.19	18.78	11.59	237.90	160.46	125.41
S4	1.52	0.95	0.38	120.15	85.76	41.76	6.06	4.41	2.57	11.02	13.52	15.64	48.63	31.61	22.42	385.79	210.65	143.30
S5	3.28	1.52	0.75	100.85	78.26	32.03	9.63	7.98	4.02	13.08	17.51	21.16	39.22	23.94	14.75	251.73	185.31	103.89
S6	2.46	1.34	0.63	137.86	98.37	53.70	8.86	5.60	2.50	13.39	15.46	22.30	44.35	35.80	23.61	352.58	241.72	158.00
S7	1.07	0.82	0.47	100.72	59.27	37.74	5.09	3.44	1.38	12.86	18.14	20.47	37.03	21.17	11.98	248.26	188.54	126.26
S8	1.22	1.15	0.51	101.54	63.62	33.81	7.51	6.72	2.09	16.47	14.05	16.31	41.61	28.22	13.03	205.98	178.18	107.35
S9	3.05	1.91	1.05	125.56	89.34	52.00	8.37	7.09	3.60	14.54	17.11	18.87	31.58	20.49	14.80	241.80	182.72	124.28
S10	2.09	1.65	0.89	123.42	83.58	40.03	9.54	5.86	2.51	17.25	19.77	23.75	45.35	28.19	15.00	254.94	155.56	95.24
Range	1.07– 3.28	0.82– 1.91	0.38– 1.06	100.72– 154.18	59.27– 101.77	26.17– 78.95	5.09– 9.63	3.44– 8.21	1.38– 4.90	11.02– 17.25	12.04– 19.77	15.64– 23.75	31.58– 53.91	18.78– 36.94	11.59– 25.75	205.98– 442.09	160.46– 284.85	103.89- 172.17
Mean	2.19	1.33	0.70	117.84	82.27	44.36	7.59	5.81	2.87	13.91	16.08	19.73	41.64	26.61	16.98	291.49	199.73	129.02
SD	0.78	0.34	0.24	18.00	13.33	14.96	1.80	1.65	1.02	2.03	2.36	2.74	6.61	6.57	5.10	76.56	39.16	24.08
Sainthia																		
S1	3.39	1.06	0.52	170.10	32.08	12.08	7.86	5.67	2.06	22.40	24.29	28.12	38.60	22.20	14.54	482.90	210.52	125.62
S2	2.75	1.52	0.54	136.07	68.65	32.86	9.63	7.80	4.13	18.14	22.77	24.25	63.16	34.17	20.42	493.26	286.06	163.41
S3	2.05	1.54	0.62	137.46	47.36	24.36	7.22	5.30	3.77	19.74	23.95	25.37	39.33	25.01	12.26	230.79	151.67	104.65
S4	1.04	0.72	0.36	146.77	59.94	37.67	8.06	4.50	3.80	20.02	21.47	26.29	52.49	32.84	26.09	283.98	165.86	109.54
S5	2.11	0.87	0.37	156.25	33.67	16.94	9.09	5.07	4.25	13.41	15.94	17.81	39.35	25.17	13.42	456.80	196.52	115.13
S6	2.38	1.31	0.65	186.64	41.61	25.61	9.84	7.69	5.73	15.80	16.89	19.95	44.49	26.03	15.28	448.94	257.93	142.24
S7	2.02	1.29	0.49	189.91	73.91	48.65	8.35	6.54	4.61	16.96	19.48	24.12	58.72	35.40	17.65	396.73	199.75	147.50
S8	2.24	1.26	0.45	139.34	34.72	17.72	6.25	3.18	2.32	14.33	18.57	21.96	47.75	23.45	12.70	294.58	189.39	108.59
S9	1.75	0.85	0.23	141.48	38.86	20.91	8.51	4.08	2.83	21.19	23.54	28.52	43.77	32.42	22.48	312.83	213.93	138.52
S10	1.64	1.01	0.69	203.78	50.94	28.94	6.37	5.81	4.27	24.48	26.20	31.40	61.04	39.72	23.68	507.09	306.77	189.48
Range	1.04– 3.39	0.72– 1.54	0.23– 0.69	136.07– 203.78	32.08– 73.91	12.08– 48.65	6.25– 9.84	3.18– 7.80	2.06– 5.73	13.41– 24.48	15.94– 26.20	17.81– 31.40	38.60– 63.16	22.20– 39.72	12.26– 26.09	230.79– 507.09	151.67– 306.77	104.65– 189.48
Mean	2.13	1.14	0.49	160.78	48.18	26.58	8.12	5.56	3.78	18.65	21.31	24.78	48.87	29.64	17.85	390.79	217.84	134.46
SD	0.64	0.28	0.14	25.07	14.94	10.93	1.24	1.48	1.11	3.57	3.43	4.11	9.41	5.98	5.00	101.45	50.45	27.37

Table 5. Vertical distribution different forms of sulphur (mg kg^{-1}) in soils of Md. Bazar block of Birbhum District, West Bengal

Sample	Ws-S at depth (cm)			Org-S at depth (cm)			Sulph-S at depth (cm)			Ads-S at depth (cm)			Hs-S at depth (cm)			Tot-S at depth (cm)		
	0–20	**20–40**	**40–60**	**0–20**	**20–40**	**40–60**	**0–20**	**20–40**	**40–60**	**0–20**	**20–40**	**40–60**	**0–20**	**20–40**	**40–60**	**0–20**	**20–40**	**40–60**
Md. Bazar																		
S1	1.32	0.95	0.37	178.21	83.28	32.78	4.32	3.61	2.10	25.49	28.01	29.30	52.35	33.26	18.13	320.22	252.05	165.61
S2	2.50	1.04	0.56	152.48	31.61	17.56	7.45	3.80	2.08	19.24	25.67	26.43	44.24	28.23	13.02	279.75	202.72	117.40
S3	2.02	1.45	0.44	144.44	60.11	25.06	3.72	2.86	1.72	22.83	24.49	28.55	50.47	36.07	18.86	436.39	235.52	139.64
S4	2.81	1.41	0.49	181.39	44.60	20.37	6.15	4.14	2.75	18.12	22.19	25.47	54.91	38.90	23.69	460.29	217.33	109.53
S5	2.04	1.85	0.58	151.91	90.42	46.64	5.72	4.70	2.19	22.51	24.66	27.99	66.24	36.23	14.02	418.07	245.41	140.12
S6	1.82	1.03	0.25	123.60	48.21	23.31	4.34	2.29	1.76	23.90	25.61	26.13	41.10	24.09	12.88	387.47	200.59	121.23
S7	3.01	1.51	0.42	186.05	52.11	27.35	6.19	3.67	2.06	20.05	23.20	26.30	68.08	32.46	16.25	511.32	191.18	102.49
S8	1.95	1.19	0.37	142.78	66.46	30.42	4.46	3.68	2.27	22.43	24.29	27.14	56.52	34.51	21.30	404.28	229.43	167.58
S9	2.32	1.73	0.58	133.92	63.16	28.31	4.61	3.78	2.79	19.29	22.26	25.70	38.79	27.79	16.08	330.58	218.18	113.51
S10	1.23	0.82	0.36	191.62	76.10	32.64	5.63	2.41	1.07	24.57	26.92	28.58	57.50	36.86	24.28	485.43	186.59	104.47
Range	1.23–3.01	0.82–1.85	0.25–0.58	123.60–191.62	31.61–90.42	17.56–46.64	3.72–7.45	2.29–4.70	1.07–2.79	18.12–25.49	22.19–28.01	25.47–29.30	38.79–68.08	24.09–38.90	12.88–24.28	279.75–511.32	186.59–252.05	102.49–167.58
Mean	2.10	1.30	0.44	158.64	61.60	28.45	5.26	3.49	2.08	21.84	24.73	27.16	53.02	32.84	17.85	403.38	217.90	128.15
SD	0.58	0.34	0.11	23.84	18.25	8.12	1.15	0.76	0.50	2.52	1.90	1.36	9.81	4.73	4.17	75.04	22.59	23.98

Table 6. Relationship between forms of sulphur with soil physico-chemical properties at various soil depth

S Forms	Soil properties/Soil depth					
	0-20 cm soil depth					
	pH	**OC**	**CEC**	**Sand**	**Silt**	**Clay**
Ws-S	0.431**	0.295	0.09	-0.089	0.13	0.042
Org-S	-0.119	0.636**	0.03	-0.386**	0.327*	0.383**
Sulph-S	0.325*	0.305*	0.329*	-0.21	0.279*	0.121
Ads-S	-0.022	0.331*	0.026	-0.311*	0.196	0.368**
Hs-S	-0.207	0.599**	0.065	-0.133	0.026	0.207
Tot-S	-0.103	0.584**	0.059	-0.283*	0.248	0.274
	20-40 cm soil depth					
Ws-S	0.131	0.213	0.219	-0.011	0.038	0.011
Org-S	-0.063	0.114	0.349*	-0.034	0.09	0.126
Sulph-S	0.450**	0.165	0.354*	-0.288*	0.221	0.306*
Ads-S	-0.071	0.566**	-0.06	-0.282*	0.204	0.308*
Hs-S	-0.256	0.588**	0.232	-0.243	0.194	0.253
Tot-S	-0.068	0.407**	0.431**	-0.298*	0.141	0.383**
	40-60 cm soil depth					
Ws-S	0.074	0.119	0.387**	-0.236	0.241	0.199
Org-S	-0.071	0.274	0.364**	-0.125	0.300	0.223
Sulph-S	0.423**	0.115	0.349**	-0.263	0.228	0.251
Ads-S	-0.055	0.534**	0.092	-0.428**	0.241	0.506**
Hs-S	-0.141	0.504**	0.308*	-0.374**	0.239	0.422**
Tot-S	0.007	0.333*	0.461**	-0.401**	0.261	0.448**

**, ** Significant at 0.05 and 0.01 probability levels, respectively*

Table 7. Inter-relationship between forms of sulphur at various soil depths

Forms	Ws-S	Org-S	Sulph-S	Ads-S	Hs-S	Tot-S
	0-20 cm soil depth					
Ws-S	1.000					
Org-S	0.442**	1.000				
Sulph-S	0.440**	0.097	1.000			
Ads-S	-0.047	0.489**	-0.233	1.000		
Hs-S	0.011	0.531**	-0.056	0.296*	1.000	
Tot-S	0.237	0.781**	0.24	0.398**	0.475**	1.000
	20-40 cm soil depth					
Ws-S	1.000					
Org-S	0.440**	1.000				
Sulph-S	0.370**	0.206	1.000			
Ads-S	-0.116	0.283*	-0.099	1.000		
Hs-S	0.176	0.244	0.117	0.190	1.000	
Tot-S	0.220	0.344*	0.233	0.139	0.441**	1.000
	40-60 cm soil depth					
Ws-S	1.000					
Org-S	0.153	1.000				
Sulph-S	0.188	0.217	1.000			
Ads-S	-0.199	-0.093	0.150	1.000		
Hs-S	0.064	0.361*	0.335*	0.259	1.000	
Tot-S	0.209	0.272	0.222	0.288*	0.345*	1.000

**, ** Significant at 0.05 and 0.01 probability levels, respectively*

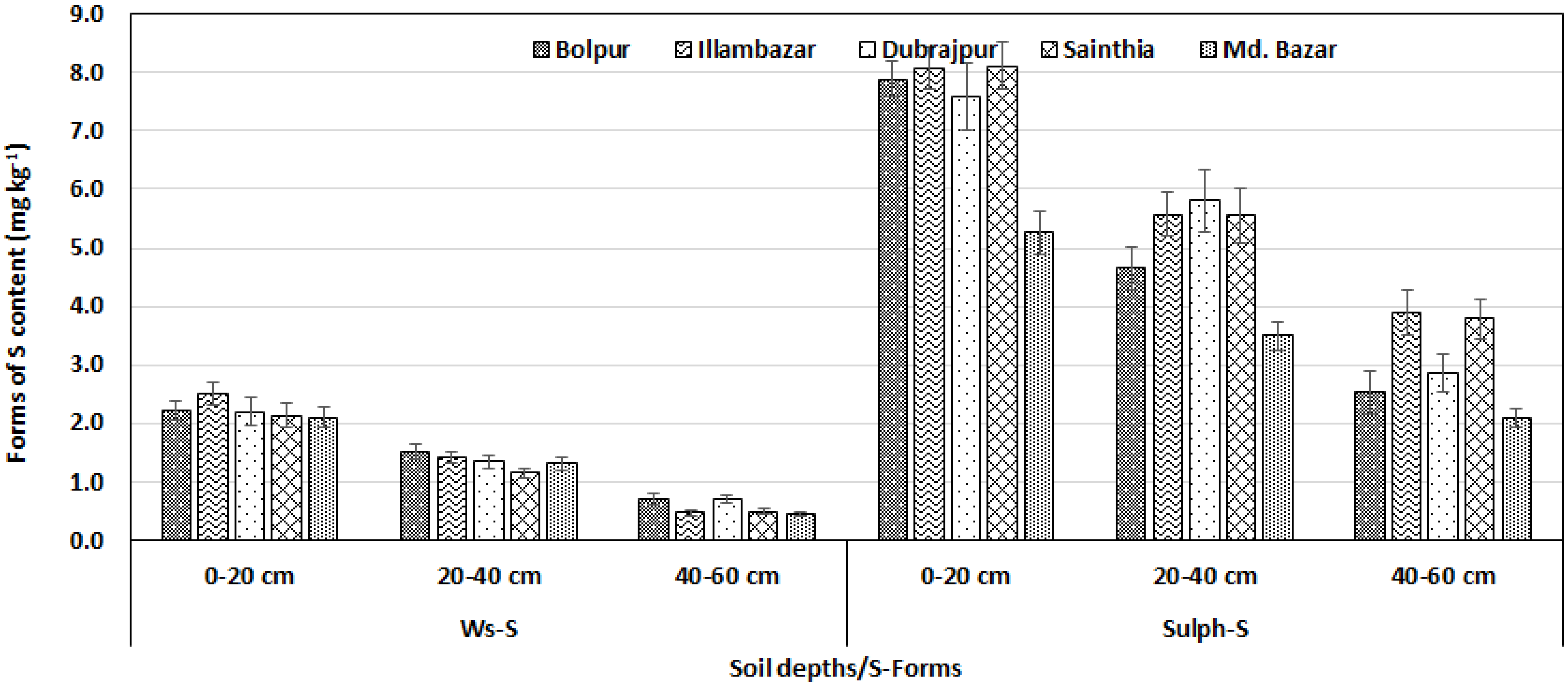

Fig. 1. Depth-wise distribution of water soluble sulphur (Ws-S) and sulphate sulphur (Sulph-S) forms of soil sulphur in the study area

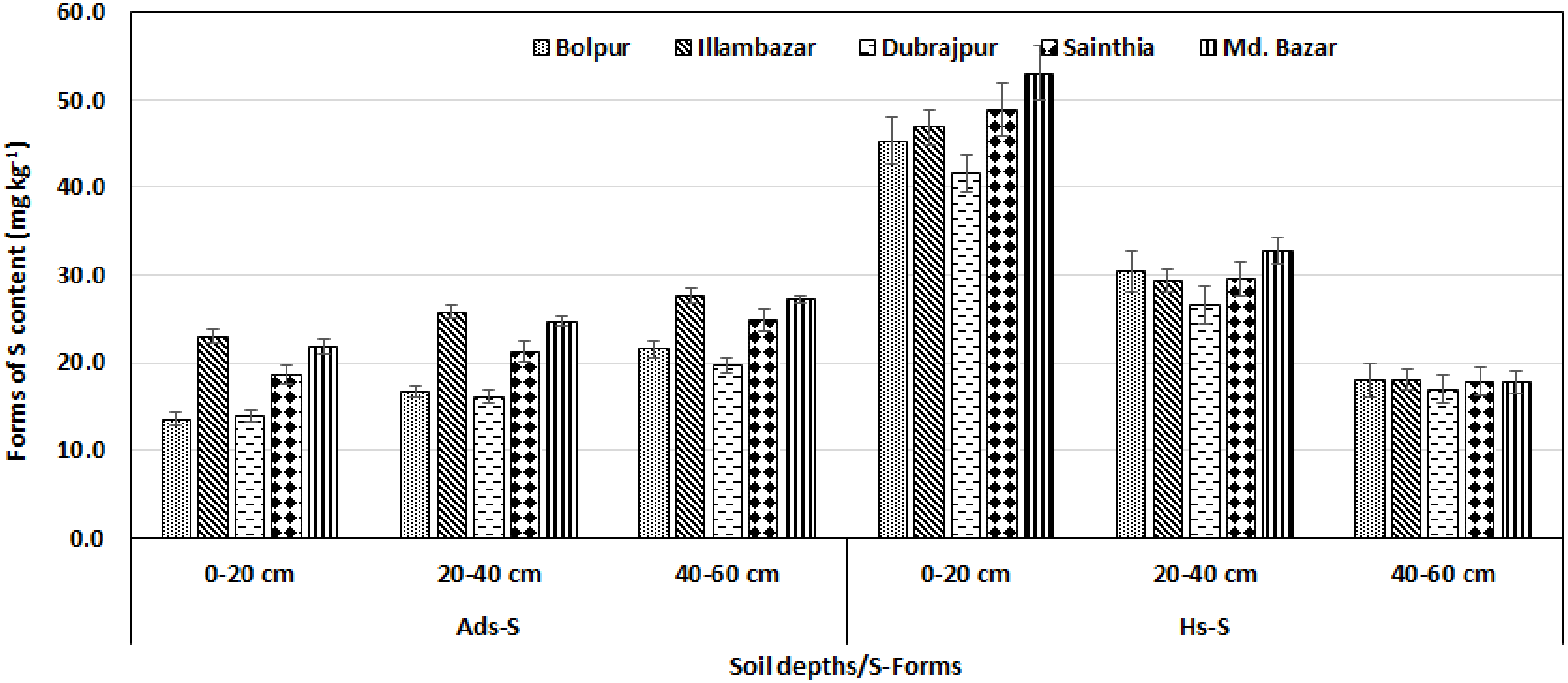

Fig. 2. Depth-wise distribution of adsorbed sulphur (Ads-S) and heat soluble sulphur (Hs-S) forms of soil sulphur in the study area

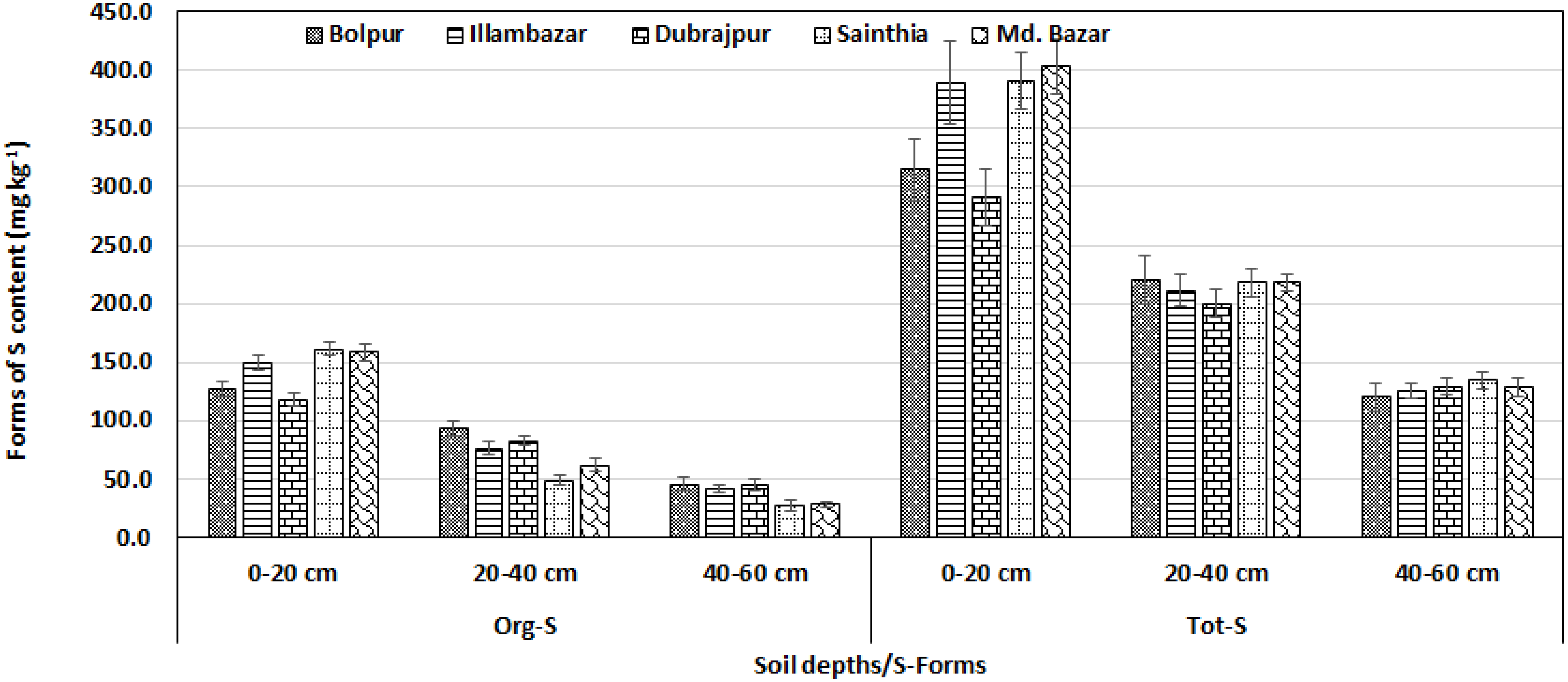

Fig. 3. Depth-wise distribution of organic sulphur (Org-S) and total sulphur (Tot-S) forms of soil sulphur in the study area

3.2.1 Water soluble sulphur (Ws-S)

In the surface layer, the water soluble sulphur (Ws-S) ranged from 1.04 to 3.39, with a mean value of 2.22 mg kg^{-1}; in the mid-surface layer, it ranged from 0.72 to 2.25, with a mean of 1.34 mg kg^{-1}; and in the bottom layer, it ranged from 0.21 to 1.22, with a mean value of 0.56 mg kg^{-1}. Surface soils of the Sainthia block had the highest amount of water-soluble sulphur, whereas the subsurface layer of the Illambazar block had the lowest amount. Water soluble sulphur contributes a small fraction of total sulphur (< 1 %). The relatively low concentration of this fraction might be due to the leaching of sulphate from soil layers. Similar observations were also made by Suri et al. [32]. In comparison to subsurface soil, surface soil had a higher concentration of water soluble sulphur. The decrease in Ws-S with depth was also found by Sankhyan et al. [33]. The average values of water soluble sulphur are in agreement with the observations of Kumar and Singh [34], Bandyopadhyay and Chattopadhyay [35], Ghosh et al. [17].

Water soluble sulphur (Ws-S) was found to have a significant and positive correlation with organic carbon, CEC, silt and clay content, whereas it was significantly and positively correlated with pH (r= 0.431**) in the surface layer. A negative and non-significant correlation was observed between Ws-S and sand content in all three depths. In the lower depth soil CEC showed a positive and significant correlation (r= 0.387**). Similar observations also reported by Ghosh et al. [17], Rajkonwar et al. [36], Kundu et al. [16], Suri et al. [32]. The positive correlation with organic C may due to the importance of organic matter on sulphur availability which was reported by Borkotoki and Das [18], Paul and Mukhopadhyay [11] and Bandyopadhyay and Chattopadhyay [35].

3.2.2 Organic Sulphur (Org-S)

Crop plants primarily obtain S from organic sources and it's the major contributor of total S, but this S must first be converted to sulphate through mineralization. The organic sulphur (Org-S) content in surface soils under study varied, ranging from 98.11 to 203.78 with an average value of 142.83 mg kg^{-1} whereas in mid-surface and subsurface soils it ranged from 31.61 to 125.27 mg kg^{-1} and 12.08 to 78.95 mg kg^{-1} respectively. The highest mean values of organic sulphur in surface (0–15 cm depth) obtained in Sainthia (160.78 mg kg^{-1}) and Md. Bazar (158.64 mg kg^{-1}) may be due to the high organic carbon content of these blocks. Similar observations also reported by Chattopaddhyay and Ghosh [30]. In comparison to subsurface soil, surface soil has a higher concentration of organic sulphur. The decrease in organic carbon may be accountable for this tendency in organic sulphur [37,25,38].

The surface soils showed a significant and positive correlation with organic carbon (r=0.636**), silt (r=0.327**) and clay content (r=0.383**). However, it showed a negative and significant correlation with sand (r= -0.386). The soil pH showed a negative correlation with Org-S throughout the layer. The mid-surface and subsurface soils correlated significantly and positively with CEC (r=0.349** and r= 0.364**). These results are in conformity with earlier reports of Paul and Mukhopadhyay [11], Rajkonwar et al. [36] and Suri et al. [32]. The results indicated that Org-S content of the soil greatly affected by organic carbon content and soil texture [26,39,21].

3.2.3 Sulphate sulphur (Sulph-S)

From a nutritional perspective, the sulphate fraction of S is crucial, and it may serve as a useful indicator for evaluating the availability of S to plants. This fraction constituted more than Ws-S to total S. The average sulphate sulphur content in surface soils varied from 7.89 ± 0.95 mg kg^{-1}, 8.08 ± 1.11 mg kg^{-1}, 7.59 ± 1.89 mg kg^{-1}, 8.12 ± 1.24 mg kg^{-1}, and 5.26 ± 1.15 mg kg^{-1} respectively in the soils of Bolpur, Illambazar, Dubrajpur, Sainthia and Md. Bazar blocks. It varied from 2.29 to 8.21 mg kg^{-1} and from 1.07 to 2.79 mg kg^{-1} in the mid-surface and subsurface, respectively, in the soils under investigation. Similar to water soluble and organic fraction, sulphate sulphur fraction decreased with increasing depth. The higher levels of sulfate S in surface soils may have resulted from increased microbial and plant activity, which led to an accumulation of organic matter. These findings are in good agreement with Srinivasarao et al. [38], Ghosh et al. [17], Chattopaddhyay and Ghosh [30] and Kour et al. [39].

This form of S exhibited a positive and significant relationship with soil pH (r = 0.325*), (r = 0.450**), and (r = 0.423**) at the surface, mid-surface and subsurface respectively. Similar findings were also reported by Kour et al. [39]. This form of S possessed a positive and significant relationship with OC (r = 0.305*) in surface soils and with CEC in all three depths. Both clay and silt content showed a positive correlation with this form, while a negative correlation was noted with sand content. The considerable positive association between sulphate S and both clay and organic carbon shows that these soils' ability to supply sulphur depends heavily on both of these factors. These findings line up with those of Bandyopadhyay and Chattopadhyay [35], Ghosh et al. [17], Kour and Jalai [49], Chattopaddhyay and Ghosh [30], Rajkonwar et al. [36], and Suri et al. [32].

3.2.4 Adsorbed Sulphur (Ads-S)

Adsorbed S in all the soils under study varied widely and ranged from 10.06 to 32.97 mg kg^{-1} at different soil depths and constituted on average 11.30 % of total S (Table 2). Unlike other fractions, this form of S increases with increasing soil depth. In subsoil, it ranged from 14.12 to 32.97 mg kg^{-1} whereas in surface soil, it varied from 10.06 to 26.96 mg kg^{-1}. Similar findings also reported by Srinivasarao et al. [38]. According to Mishra et al. [40], an increase in clay content with depth may the cause of the increase in adsorbed S. It may due to retention of sulphate on the surface of sequioxides and on the edges of kaolinitic type of clays [41].

In all three soil layers (0–20 cm, 20–40 cm, and 40–60 cm), adsorbed S correlated negatively with pH and significantly negatively with sand (r= -0.311*, r= -0.282* and r= -0.428**). Sulphate adsorption is a pH-dependent process, and it was evident that raising soil pH would cause a decline in the amount of sulphur in this form due to lesser sulphate adsorption in soils and concurrent leaching losses [42,43]. Adsorbed S was positively correlated with silt content and positively and significantly with clay content in surface (r = 0.368**), mid-surface (r =0.308*) and in subsurface soils (r = 0.506**). The organic matter content of the soil also showed a positive and highly significant correlation with adsorbed S, the values are r = 0.331*, r = 0.566** and r = 0.534** in surface to subsurface layers, respectively. The adsorption of sulphate on the finer fractions of soil and organic matter could account for the positive relationship of adsorbed S with those fractions and the dominant role organic matter plays in sulphate sorption in these soils [44]. These findings are consistent with reports by Kour et al. [39], Rajkonwar et al. [36], and Srinivasarao et al. [38].

3.2.5 Heat soluble sulphur (Hs-S)

This portion of S, also known as mineralizable S, accounts about 13.17 % of total S in surface soils. In comparison to water soluble S, sulphate-S, and adsorbed-S, heat soluble S content was higher in the soils under study. Among the blocks, the surface soils of Md. Bazar block observed the highest amount of heat soluble S (68.08 mg kg^{-1}) while the lowest value observed in subsurface soils of Bolpur block (10.06 mg kg^{-1}). These findings are similar to finding of Kundu et al. [16]. Higher amount of heat soluble S is attributed to release of additional amount of S from organic as well clay minerals on wet and dry heating of the soil during extraction.

A significant positive correlation between heat soluble S and organic carbon was observed for all three depths, with values; of r = 0.599**, r =0.588** and r = 0.504** respectively. The heat soluble S also showed positive correlation with CEC, silt and clay content, whereas negative correlation with sand content. In subsurface soils, a significant and positive correlation was observed with CEC (r = 0.308*) and clay content (r = 0.422**), but a negative and significant correlation with sand content (r = -0.374**). These results are in concurrence with the findings of Sharma and Jaggi [45], Basumatary et al. [46], Borkotoki and Das [18], Paul and Mukhopadhyay [11], Rajkonwar et al. [36].

3.2.6 Total S (Tot-S)

Total S content, which indicates the reserve pool of this element in soil, ranged from 205.98 to 545.04 mg kg^{-1} in surface soils. Among the blocks, by considering the average values of three depths, soils from the Md. Bazar block recorded the highest content of total S (249.81 mg kg^{-1}) while the lowest was found in the Dubrajpur block (206.74 mg kg^{-1}).The average values in the surface layers varied from 314.53 ± 84.80, 389.24 ± 113.43, 291.49 ± 76.56, 390.79 ± 101.45 and 403.38 ±75.04 mg kg^{-1} in soils of Bolpur, Illambazar, Dubrajpur, Sainthia and Md. Bazar blocks. Wide variation in total S may due to variation in soil pH, organic carbon and clay content. Similar results also reported by Kumar et al. [47], Srinivasarao et al. [38], Ghosh et al. [17], Kundu [26], Paul and Mukhopadhyay [11], Suri et al. [32].

Total S has significant positive correlation with organic carbon (r= 0.584**), significant and negative correlation with sand content (r = -

0.283*) in surface layers, whereas it has a significant positive correlation with organic carbon (r = 0.333*), CEC (r= 0.431**) and clay content (r= 0.383**) in mid-surface layers. Similar relationships were also observed in subsurface layer, indicating the strong association of these soil properties with total S and implying that most of the sulphur is greatly influenced by organic matter. The results are in accordance with Bhogal et al. [48], Bandyopadhyay and Chattopadhyay [35], Srinivasarao et al. [38], Kour and Jalai [49], Borkotoki and Das [18], Kour et al. [39], Paul and Mukhopadhyay [11], Rajkonwar et al. [36], Roshini et al. [50] and Suri et al. [32].

3.3 Inter-relationship between Forms of Sulphur of Lateritic Soils of West Bengal

Among fractions, water soluble sulphur had a significant and positive correlation with organic S and sulphate S in both surface (r = 0.442** r= 0.440**), and mid-surface (r = 0.440** and r= 0.370**) layer soils (Table 7). It was also noted that organic sulphur exhibited a significant positive relationship with adsorbed sulphur (r=0.489**), heat soluble sulphur (r=0.531**) and total sulphur (r=0.781**) in surface soils. The adsorbed sulphur showed a negative correlation with water soluble sulphur and sulphate S. Total sulphur exhibited a positive relationship with all other sulphur forms, indicating that all fractions of sulphur in these soils maintained a dynamic equilibrium. Similar relationships among various forms of S were also reported by Srinivasarao et al. [38], Ghosh et al. [17], Kundu [26], Borkotoki and Das [18], Basumatari et al. [22], Paul and Mukhopadhyay [11] and Roshini et al. [50].

4. CONCLUSIONS

Understanding the vertical distribution of various forms of S in soils and their relationship between soil physicochemical properties will be useful for managing it to maximise crop yields in the rice-growing lateritic soils of West Bengal, India. The investigation revealed that, except for adsorbed S, most forms decreased with soil depth. The largest and smallest components of the total S were the organic and water soluble forms. The analysis of the data showed that the different forms of sulphur were in the following order: total S > organic S > heat soluble S > adsorbed S > sulphate S > water soluble S. Their availability was impacted by the amount of organic matter, the texture of the soil, and the reaction of the soil. The inter-relationships between the forms within them revealed that all sulphur fractions in these soils maintained a dynamic equilibrium.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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