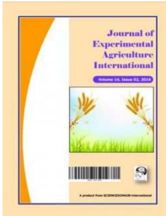

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Distribution of Sulphur in Some Soils of Meghalaya

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Authors' contributions

This work was carried out in collaboration between all authors. Author AS designed the study, performed the statistical analysis and wrote the first draft of the manuscript. Authors JM and AD managed the analyses of the study and wrote the protocol. Author PB managed the literature searches. All authors read and approved the final manuscript.

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ABSTRACT

A study was undertaken to generate information on the distribution of different forms of sulphur in the soils of Meghalaya. Surface soils (0-15 cm) were collected from 10 (ten) different locations comprising 3 districts viz., Jaintia hills, East Khasi, and Ribhoi districts of the State of Meghalaya belonging to three soil orders. Soils from Meghalaya were acidic in nature with mean pH value being 5.49. The organic carbon contents were in general medium with mean value of 0.703 and texturally the soils varied from Sandy to Clay loam. The available P was in general medium to high. The soils of Meghalaya have adequate available S.

The water soluble S had a mean value of 6.19 mg kg^{-1} soil for Meghalaya. Sulphate S varied between 2.89 and 4.02%. The fraction is low probably because of coarse soil texture thereby leading to its leaching. This fraction exhibited a significant negative correlation with pH and positive correlation with organic C. The adsorbed S fraction had a mean value of 15.2 mg S kg^{-1} soil contributing 2.35 to 4.23 percent of total S. The non-sulphate S had a mean value of 111.7 mg kg^{-1}

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soil and constituting the second largest fraction. The organic S averaged 324 mg kg^{-1} soil and contributed about 63.18 to 76.45% of total S. Organic S had a significant positive correlation with organic C, total N, and all form of S except non-sulphate S (NSS). The soils of Meghalya are, in particular, high in native S content.

Keywords: Meghalaya; water soluble S; sulphate S; adsorbed S; non-sulphate S; organic S.

1. INTRODUCTION

Sulphur (S) is a highly reactive element for which an elaborate biogeochemical cycle has evolved with Intermediate exchange between atmospheric, aquatic and terrestrial phases of the environment. It is required by all biotic components as a major macronutrient necessary for formation of amino acids, enzymes, vitamins and other biomolecules, and thus plays a vital role in functioning terrestrial ecosystems [1].

Sulfate (SO_4^{2-}) is the main form of inorganic S present in most soils, although some reduced S forms (e.g., elemental S, thiosulfate or sulfide) may be found in soils under predominantly anaerobic conditions [2]. The bulk of soil S (95%) in the natural and managed ecosystems, however, is found in organic forms [3,2]. The availability of S to plants is controlled by numerous factors that affect the dynamics of S fractions in the soil. In aerobic agricultural soils, many microbial-mediated processes are responsible for S transformations, including mineralization, immobilization, and oxidation [4]. Changes in the soil inorganic S pool play a major role in S dynamics because it can impact the transformation of organic S fractions in the soil [5].

North-eastern hill region of India is primarily under the acidic soil zone with high rainfall. Shifting cultivation (Jhum) is one of the predominant agricultural practices by the tribal inhabitants. The general terrain of the region being hilly and highly sloping, availability of plain or leveled land is less and hence cultivation of crops including agricultural crops like paddy, maize, ginger, etc. is taken up on the hill slopes. Very less information is available about the extent to which nutrients have been depleted across the land uses. Sulphur (S) is considered as fourth major nutrient. However, no such study has been conducted to assess the content of different S forms and the level of availability under various land uses of the region. Keeping the above in view, the study was attempted to assess content of different forms of S and their correlation with important soil properties under different soil orders of Meghalaya.

2. MATERIALS AND METHODS

The study was conducted with the soils of Meghalaya state of India. With average annual rainfall as high as 12,000 mm (470 in) in some areas, Meghalaya is the wettest place on earth. Surface soils (0-15 cm) were collected from three soil orders of Meghalaya, viz., (a) Entisol, (b) Inceptisol, and (c) Ultisol which is belonging to Jaintia hills district, East Khasi hills district, and Ri-Bhoi district, respectively (Map 1). These soils were air-dried, thoroughly mixed and ground to pass through a 2-mm sieve.

Important physico-chemical properties of these soil samples were determined. Soil pH and EC were measured in suspension of 1:2.5 :: soil: water by the method of Jackson [6]. Particle-size distribution of soils were obtained by following the International Pipette Method, as described by Piper [7]. Cation exchange capacity (CEC) was determined by centrifuging the soil with neutral normal ammonium acetate extract [6]. The available nitrogen was determined by alkaline permanganate method as described by Subbiah and Asija [8]. Organic carbon was determined by the wet oxidation method of Walkley and Black [9]. Available phosphorus [10] and potassium (1N NH_4OAc) were determined following the methods outlined by Jackson [6].

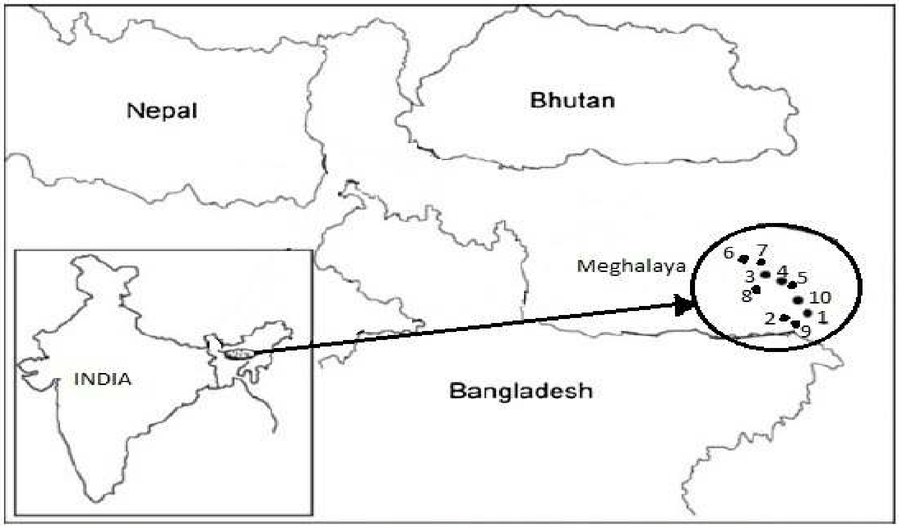
2.1 Procedure for Studying Different Forms/Fractions of Soil S

2.1.1 Water soluble sulphur

Water soluble sulphur was estimated following the method described by Freney [11].

2.1.2 Available sulphur

The available sulphur of the soils was extracted with 500 mg L^{-1} P [$Ca(H_2PO_4)_2$, H_2O] solution by following the methodologies described by Fox et al. [12].



Locations: 1. Mawryngkneng; 2. Padu; 3. Patharkhmah; 4. Madan; 5. Jowai; 6. Umkynsier; 7. Nongpoh; 8. Sohryngkham; 9. Amlarem; 10. Mustem

Map 1. Position of the localities from where soil samples were collected

2.1.3 Adsorbed sulphur

The adsorbed sulphur in soils was obtained from the difference between soluble sulphate sulphur content estimated by the method of Williams and Steinbergs [13] and the sulphur obtained by extracting the soil with monocalcium phosphate (500 mg P L^{-1}) as outlined by Fox et al. [12].

2.1.4 Sulphate sulphur

The sulphate sulphur was determined by extracting with 0.15% calcium chloride, in the ratio of 1:5, soil:extractant, as outlined by Williams and Steinbergs [13].

2.1.5 Non-sulphate sulphur

By subtracting the organic and sulphate sulphur fraction from total sulphur, the non-sulphate sulphur fraction was obtained.

2.1.6 Organic sulphur

The organic sulphur content in soils was determined by extracting the soil with sodium di-hydrogen phosphate (4.6 g L^{-1} NaH_2PO_4) in 2M acetic acid, in the ratio of 1:10 soil:extractant), as outlined by Bardsley and Lancaster [14].

2.1.7 Total sulphur

The total sulphur in the soils was extracted by sequential digestion of the soil with HNO_3, $HClO_4$, H_3PO_4 and HCl. The sulphur in the extract was estimated turbidimetrically by measuring the absorbance at 440 nm wavelength in UV-visible spectrophotometer after addition of $BaCl_2$, as described by Chesnin and Yien [15].

Statistical analysis of the important parameters will be done by following the appropriate methodologies [16]. Correlation matrix between different soil parameters and different fractions of sulphur was drawn with the help of SPSS version 20.0 software.

3. RESULTS AND DISCUSSION

3.1 Physicochemical Properties of the Experimental Soils

Some important physicochemical properties of the experimental soils and the available nutrient contents in the surface (0-15 cm) soils of ten different locations, viz., Padu, Mustem, Jowai, and Amlarem belonging to the district Jayantia hills; Mawryngkneng, Madan, and Sohryngkham belonging to East Khasi hills and Nongpoh, Patharkhmah, Umkynsier from Ribhoi district of the State of Meghalaya are presented in Table 1. These soil properties indicated that the soils from the State of Meghalaya were acidic with pH ranging from 4.33 to 6.05. The organic carbon contents (%) varied between 0.54 and 1.03 in the soils, thus representing a medium to high organic carbon status. The CEC of these soils ranged from 7.00 to 26.4 (with mean value 11.63) cmol $(p^+)\ kg^{-1}$ soil. The CEC of soils did not seem to have relation with the organic matter content in these soils (r=-0.495). The sand, silt and clay contents (%) varied from 28.6 to 90.0 (mean = 58), 4.00 to 24.0 (Mean = 14.6) and 4.00 to 49.4 (mean= 28.05), respectively, in the studied soils.

As for the available nutrients, the available N in these soils ranged between 63.9 and 183.6 mg kg^{-1} having the mean value of 116.6 mg kg^{-1}, and the available P content ranged from 3.8 to 18.8 mg kg^{-1} with the mean value of 12.2 mg kg^{-1}.The available P content was highest in the soil of Umkynsier and lowest in the Sohryngkham both being under Ultisol order. The available K was highest at the Mustem soil (146.4 mg kg^{-1}), and lowest at the Amlarem soil (41.7 mg kg^{-1}) and the values for available S were 40.83 and 22.71 mg kg^{-1} in the Sohryngkham and Jowai, respectively. It revealed that the soil of Sohryngkham was high in S and low in P. These soils of Meghalaya were all collected from uncultivated and unfertilized areas. Therefore these soils are, in general, high in native sulphur content.

3.2 Distribution of Different Forms of Sulphur and Correlation with Soil Properties

The distribution of different forms of sulphur under different soil is presented in Table 2.

3.2.1 Available and water soluble sulphur

The Water soluble S varied between 3.64 and 8.26 mg kg^{-1} with a mean value of 6.19 in the studied soils of Meghalaya showing higher contents of this fraction. The water soluble sulphur fraction mostly contains free inorganic and some organically bound sulphate [13]. Water soluble sulphur accounts for only a small fraction of total sulphur and it gives an indication of available sulphur status of soil [17]. This fraction constituted only 0.91 to 1.50 per cent of total S in the soils of Meghalaya. Sharma et al. [18] noticed that water soluble sulphur content accounted very small fraction of total sulphur, ranging from 0.83 to 24.58 per cent with an average value of 5.79 per cent in some important soil bodies of North Western Himalaya.

The water soluble S exhibited a significant negative correlation (r= –0.876**) with pH (Table 3). Kher and Singh [19] also found that water soluble sulphur was negatively correlated with pH in some mustard growing soils of North Kashmir. The available S, on the other hand, was significantly and positively correlated with the oxidizable organic carbon (r=0.681*).Indeed quite a substantial amount (63.2 to 76.45 per cent, this study) of total S came from organic source. These results are in accordance with those of Kotur and Jalali [20], Basumatary et al*.* [21] and Javed et al*.* [22]. They reported strong positive relationship of available S with soil organic carbon (SOC) content indicating that SOC is the regulating factor for availability of S in soil.

3.2.2 Sulphate sulphur

The sulphate sulphur content in soils ranged from 13.36 to 21.6 mg kg^{-1} with mean value of 17.91. Sulphate is the form of sulphur that is taken up by plant roots, although the sulphate fraction generally accounts for less that 5 per cent of the total sulphur in soil [23]. This form of S in the studied soils contributed 2.9 to 4.02 per cent of total S in the soils of Meghalaya. Singh et al. [24] reported from their studies on seven soil series of Nagaland that sulphate sulphur content was 3.3 per cent of total sulphur. Borkotoki and Das [25] reported that sulphate S contributed about 3.30, 4.30, and 6.66% in Entisols, Inceptisols, and Alfisols, respectively, of Assam and Kour et al. [26] reported 5.50 to 43.7 mg kg^{-1} with average of 20.6 mg kg^{-1} sulphate S in the mid hill region of Jammu & Kashmir, India.

The sulphate S had significant negative correlation with pH (r = –0.742**) and positive correlation with organic C (r=0.615*) and available N (r=0.635*). The increase in pH caused a reduction in anion exchange sites on the exchange complex thereby causing a reduction of adsorption of sulphate. Tiwari and Pandey [27] explained the relation as was due to the degree of H^+ and OH^- ions present on soil micelle where the former being positively charged which attract SO_4^{2-} ions and the negatively charged OH^- ions repel SO_4^{2-} ions. A negative correlation between sulphate sulphur with pH and a positive correlation with organic carbon was also observed by Kher and Singh [19].

3.2.3 Adsorbed sulphur

The adsorbed sulphur fraction ranged between 9.38 and 22.9 mg kg^{-1} (mean 16.82 mg kg^{-1}) (Table 2) contributing 2.35 to 4.23 per cent of total S. Our findings fairly agree with that of

Borkotoki and Das [25] who obtained 4.01, 1.66, and 0.74 % of total S in the form of adsorbed S in the Alfisols, Entisols and Inceptisols, respectively, of Assam, India, although Kour et al. [26] obtained on an average 67.7 mg kg^{-1} adsorbed S constituting 14.76% of total S in the soils of Jammu & Kashmir. The existing difference may be due to higher clay content, CEC of soil and low rainfall in Jammu & Kashmir region compared to Meghalaya. Adsorbed sulphur in soils showed significant positive correlation with organic carbon (r=0.652*) and available N (r=0.585*) in soils (Table 3). Significant positive correlations of adsorbed S with all forms of S reveal that there is a dynamic equilibrium exists between all these forms of S (Table 4).

3.2.4 Non-sulphate sulphur

This form of sulphur in soils varied from 83.33 to 149.5 mg kg^{-1} with mean of 119.49 (Table 2). This fraction contributed 20.89 to 28.36 per cent of total S in the soils. Such low share of this fraction to total S is quite similar to the data cited by Borkotoki and Das [25] who obtained 17.08, 13.34 and 11.19% of total S as non-sulphate in the Entisols, Inceptisols and Alfisols, respectively, of Assam. Our findings differed from those of Jat and Yadav [28] who noticed that non-sulphate sulphur content in mustard growing Entisols of Jaipur district in Rajasthan constituted approximately 66.86 per cent of total sulphur probably because sulphate occurrs as a co-crystallized impurity in calcareous soils (in the calcium carbonate) of arid and semi-arid regions which may account up to 95 per cent of the total sulphur [29]. Non-sulphate S constituted the second largest fraction contributing to the total S similar to the findings of Kour et al. [26] for the mid hill soils of Jammu & Kashmir, India. This S exhibited significant positive correlation with available N (r=0.657*) (Table 3). Non-sulphate S had found no correlation with available S and organic S (Table 4). Non-sulphate S, being largely the reduced and elemental forms, requires oxidation before it becomes available to plant. This might be the reason for having no correlation with available S. Again this inorganic form of S since originated from minerals or formed under different mechanisms in soil seems to be independent of organic matter content.

3.2.5 Organic sulphur

The organic S in the surface soil varied from 289.2 to 421.3 mg kg^{-1} with an average value 342.96 mg kg^{-1} (Table 2). This was 63.18 to 76.45 percent of total S in the given soils. In general, the soils of Meghalaya had higher content of organic S. It was observed that, in general, soil which contained high organic carbon had high organic S. These values are similar to the citations of Borkotoki and Das [25] reporting (on average) 326, 469, and 412 mg kg^{-1} organic S in the Entisols, Inceptisols and Alfisols, respectively, of Assam, contributing 79.61 to 82.34 per cent of total S. However, Organic sulphur in soils of Darjeeling area, West Bengal, ranged from 97 to 309 ppm with a mean of 204.1 ppm and accounting only 7.7 to 49.7 per cent of total sulphur in different profiles [30].

Organic S showed significant positive correlation with organic C (r=0.803**) and available S (r=0.739**) but negative correlation with available P (r=–0.670*). Organic sulphur content showed positive significant correlation with all forms of S (Table 4), except non-sulphate S.

3.2.6 Total sulphur

The total S in different soils ranged between 398.9 and 552.8 mg kg^{-1} (Table 2) with an average value of 503.3. Singh et al. [31] collected 37 soils form the Manipur state of India, where total sulphur varied between 150 and 1100 mg kg^{-1} soils. This average value of total sulphur in the Entisols and Inceptisols of Assam were 410 mg kg^{-1} and 570 mg kg^{-1}, respectively, and such lower amount of total S in Entisols was accounted for by the lesser quantity of some dominant of soil components such as organic carbon and clay [25]. Total S in the mid-hill zone of the Jammu & Kashmir region of India was also varied between 193 and 774 mg kg^{-1} with average value of 459 mg kg^{-1} [26].

Total S had significant negative correlation with pH (r= –609*) but positive correlation with organic carbon (r = 0.668*), available N (r = 0.591*) and available S (r = 0.960**) (Table 3). The positive correlation with organic carbon was found because organic S is the major constituent of total S and organic S has significant positive relationship with soil organic C (Table 4). Several researchers [32,33] reported such significant negative correlation with pH and positive relation with organic carbon. Das et al. [34] and Dhamak et al. [35] also reported significant positive correlation of soil organic carbon with different forms of S. Total S was found to have significant positive correlation with all forms of S (Table 4) which is indicative of dynamic equilibrium in soils.

Table 1. Some important physico-chemical properties of selected soils

Soil properties	Locations									
	Padu	**Mustem**	**Mawryngkneng**	**Nongpoh**	**Patharkhmah**	**Madan**	**Amlarem**	**Jowai**	**Umkynsier**	**Sohryngkham**
Soil order	Inceptisol	Entisol	Ultisol	Ultisol	Ultisol	Ultisol	Inceptisol	Inceptisol	Ultisol	Ultisol
pH (1:2.5)	5.38	4.33	6.2	5.19	6.05	4.98	5.45	5.89	5.73	5.69
EC / (dS m^{-1}) (1:2.5)	0.17	0.12	0.06	0.1	0.11	0.09	0.13	0.16	0.2	0.21
CEC (cmol (p^+) kg^{-1})	12.6	14.8	10.4	11.4	10.7	7	26.4	8.4	11	4.8
Oxidizable organic carbon (%)	0.56	0.77	0.72	0.61	0.8	0.82	0.59	0.54	0.84	1.03
Organic Matter (%)	1.26	1.73	1.63	1.37	1.80	1.85	1.33	1.21	1.89	2.32
Sand (%)	90	40.6	72.6	28.6	50.5	58.56	86.56	46	40.56	66
Silt (%)	6	20	10	22	18	16	4	24	16	10
Clay (%)	4	39.4	17.4	49.4	38	25.44	9.44	30	43.44	24
Water holding capacity (%)	22.4	42.4	28.1	44.1	34.8	26.89	36.45	41.47	41.53	36.69
Total N (g kg^{-1})	0.95	1.3	1.22	1.03	1.35	1.38	1	0.91	1.42	1.74
Available N (mg kg^{-1})	172.8	118.8	91.9	183.6	169.2	82.5	70.8	63.9	103.1	110
Available P (mg kg^{-1})	14.3	11.9	12.2	15.3	11.2	12.5	7.5	15.0	18.8	3.8
Available K (mg kg^{-1})	114.3	146.4	69.2	113.4	86.6	60.0	41.7	84.5	58.7	125.1

Table 2. Different sulphur fractions in the soils of Meghalaya

Soils	Soil order	Forms of sulphur (mg kg^{-1})						
		WSS	**Avail S**	**SUL-S**	**ADS-S**	**NON-S**	**ORG-S**	**TOT-S**
Mawryngkneng	Ultisol	5.22(0.97)	38.54(7.13)	15.67(2.90)	22.87(4.23)	149.5(27.64)	347.6(64.27)	540.86
Patharkhmah	Ultisol	5.34(0.97)	38.67(7.05)	16.65(3.03)	22.02(4.01)	133.6(24.34)	371.2(67.64)	548.81
Madan	Ultisol	7.65(1.48)	34.78(6.73)	17.68(3.42)	17.1(3.31)	129.2(25.00)	345.2(66.79)	516.83
Umkynsier	Ultisol	5.86(1.15)	37.77(7.42)	20.46(4.02)	17.31(3.40)	121.8(23.93)	343.6(67.50)	509.03
Nongpoh	Ultisol	7.36(1.50)	35.5(7.25)	19.64(4.01)	15.86(3.24)	129.2(26.39)	317.5(64.85)	489.56
Sohryngkham	Ultisol	7.32(1.32)	40.83(7.39)	21.64(3.91)	19.19(3.47)	83.33(15.07)	421.3(76.45)	552.78
Amlarem	Inceptisol	4.93(1.12)	24.24(5.51)	13.56(3.08)	10.68(2.43)	91.92(20.91)	318.5(72.45)	439.59
Padu	Inceptisol	6.29(1.24)	36.59(7.22)	19.86(3.92)	16.73(3.30)	143.8(28.36)	320.3(63.18)	506.98
Jowai	Inceptisol	3.64(0.91)	22.74(5.70)	13.36(3.35)	9.38(2.35)	83.33(20.89)	289.2(72.50)	398.91
Mustem	Entisol	8.26(1.56)	37.63(7.10)	20.53(3.87)	17.1(3.22)	129.2(24.36)	355.2(66.98)	530.29
Maximum		8.26	40.83	21.64	22.87	149.5	421.3	552.78
Minimum		3.64	22.74	13.36	9.38	83.33	289.2	398.91
Mean		6.187	34.73	17.905	16.824	119.488	342.96	503.364
Stdev		2.063	6.171	4.592	5.486	29.47	56.29	86.84

WSS= Water soluble S, SUL-S= Sulphate S, ADS-S= Adsorbed S, NON-S= Non-sulphate S, ORG-S= Organic S, TOT-S= Total S
Figures in parenthesis represent Percent contribution to total S

Table 3. Correlation of different forms of sulphur with soil properties

Soil properties	Forms of sulphur						
	Avail S	WSS	SUL-S	ADS-S	NON-S	ORG-S	TOT-S
pH	-0.043	-0.876**	-0.742**	-0.382	-0.506	-0.545	-0.609*
CEC	-0.483	0.147	0.100	-0.046	0.013	0.156	0.112
OC	0.681**	0.568	0.615*	0.652*	0.176	0.803**	0.668*
Sand	-0.129	0.02	0.077	0.166	0.120	0.202	0.187
Silt	-0.063	-0.249	-0.290	-0.344	-0.265	-0.419	-0.101
Clay	0.239	0.079	0.028	-0.023	-0.015	-0.054	-0.038
Total N	0.680**	0.569	0.617*	0.655*	0.179	0.806*	0.671*
Avail N	0.538	0.559	0.635*	0.585*	0.657*	0.439	0.591*
Avail P	-0.062	-0.423	-0.398	-0.402	-0.005	-0.670*	-0.193
Avail K	0.440	0.330	0.303	0.093	0.054	0.148	0.111

**Significant at P=0.05*
***Significant at P=0.01*

Table 4. Correlation among different forms of S in the studied soils

	WSS	SUL-S	ADS-S	NON-S	ORG-S	TOT-S
Avail S	0.618	0.782**	0.899**	0.561	0.739**	0.960*
WSS		0.911**	0.697*	0.649*	0.803**	0.857**
SUL-S			0.751**	0.626*	0.843**	0.881**
ADS-S				0.804*	0.855**	0.947**
NON-S					0.518	0.774**
ORG-S						0.942**

WSS= Water soluble S, SUL-S= Sulphate S, ADS-S= Adsorbed S, NON-S= Non-sulphate S, ORG-S= Organic S, TOT-S= Total S
**Significant at P=0.05; **Significant at P=0.01*

4. CONCLUSION

The soils of Meghalaya are high in native S probably because of large deposit of coal and minerals rich in sulphur. The collected soils were from uncultivated and generally from mountainous regions. So far, the reports on soil sulphur status of the Meghalaya state were not available. In that sense, it is an attempt to report the S fractions in the soils and their relationship with different soil properties of the state. Correlation studies revealed that organic S is the main pool controlling the S dynamics in soil.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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