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Research article

RESPONSE OF RAPESEED (*Brassica juncea* L.) TO VARIOUS SOURCES AND LEVELS OF SULPHUR IN RED AND LATERITIC SOILS OF WEST BENGAL, INDIA

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ABSTRACT: Field experiments conducted on rapeseed (*Brassica juncea* L.) during 2000-2001 and 2001-2002 in a typical lateritic soil (Alfisol) of West Bengal, India revealed that sources viz. single superphosphate, phosphogypsum, pyrites and elemental S and levels of sulphur (0, 20, 40, 60 kg S ha^{-1}) have significant influence on grain yield, total biological yield, sulphur concentration in grain and stover, total sulphur uptake, grain protein content, oil content and oil yield. The maximum grain yield (16.39 and 17.15 q ha^{-1}) was recorded with SSP followed by phosphogypsum (16.08 and 16.91 q ha^{-1}) and pyrites (15.23 and 16.12 q ha^{-1}) @ 45 kg S ha^{-1} during both the years. The lowest yield was observed with elemental S. S concentration in grain and stover of rapeseed increased with increasing levels of S. The highest S uptake (28.51 and 29.13 kg S ha^{-1}) @ 60 kg S ha^{-1} was noticed with single superphosphate followed by phosphogypsum (25.95 and 28.92 kg S ha^{-1}), pyrites (24.92 and 26.32 kg S ha^{-1}) and elemental S (22.37 and 23.11 kg S ha^{-1}) during both the years. The highest oil yield (6.93 and 7.37 q ha^{-1}) was obtained at the application of 45 kg S ha^{-1} with single superphosphate followed by phosphogypsum (6.78 and 7.25 q ha^{-1}) and pyrites (6.37 and 6.89 q ha^{-1}) during both the years. However, the decreasing trend of oil content in seeds besides higher oil yield due to higher levels of S application to soil was noticed. Amongst the various sources of S tested, single superphosphate was the best with respect to grain yield, oil yield and protein content, S recovery and crop response followed by phosphogypsum, pyrites and elemental S. However, elemental S also responded well at higher level (i.e. 60 kg S ha^{-1}) under consideration. Sulphur sources also improve the availability of S in soils after the harvest of the crop.
Key words: Rapeseed, sulphur ferilisers, yield, response, uptake, oil content, protein content

INTRODUCTION

Sulphur is the fourth most important nutrient after nitrogen, phosphorus and zinc for Indian agriculture [1]. Sulphur is best known for its role in the synthesis of proteins, oils, vitamins and flavoured compounds in plants. Three amino acids viz. Methionine (21%S), Cysteine (26%S), and Cystine (27%S) contain S which are the building blocks of proteins. About 90% of sulphur is present in these amino acids [2]. Sulphur is also involved in the formation of chlorophyll, glucosides and glucosinolates (mustard oils), activation of enzymes and sulphydryl (SH-) linkages that are the source of pungency in onion, oils, etc. [3]. Adequate sulphur is therefore very much crucial for oil seed crops. Sulphur is also a constituent of vitamins biotine and thiamine (B_1) and also of iron sulphur proteins called ferrodoxins. Sulphur is associated with the production of crops of superior nutritional and market quality. Sulphur deficiencies have been reported from over 70 countries world wide including India. Sulphur deficiencies in India are widespread and scattered throughout 120 districts out of 400 districts [4]. Deficiency of sulphur in Indian soils is on increase due to intensification of agriculture with high yielding varieties and multiple cropping coupled with the use of high analysis sulphur free fertilizers along with the restricted or no use of organic manures have accrued in depletion of the soil sulphur reserve. Crops generally absorb sulphur and phosphorus in similar amounts. On average, the sulphur absorbed per tonne of grain production is 3-4 kilograms in cereals, 8 kilograms in pulses, and 12 kilograms in oilseeds [4]. Soils, which are deficient in sulphur, cannot on their own provide adequate sulphur to meet crop demand resulting in sulphur deficient crops and sub-optimal yields.

In India, red and lateritic soils cover an area of about 91 million hectares. These soils are derived from granite, gneiss, schist, and sand stone, shale parent rocks on gently to undulating geomorphic surfaces. These soils are dominantly classified as Alfisols, Ultisols and Oxisols occurring in association with Entisols and Inceptisols. Basically these soils are well drained and acidic with lower cation exchange capacity and organic matter content and have mixed or kaolinitic clay mineralogy enriched with sesquioxides [5]. Red and Lateritic soils occupy an area of about 28,000 sq km in West Bengal, which is about 28 per cent of the total geographical area of the state [6]. In fact, the red, laterite and associated soils of Eastern India are acidic in soil reaction, light textured, low in organic matter and P and are often deficient in S [7]. In West Bengal, six districts viz. Birbhum, Burdwan, Murshidabad, Midnapore, Nadia and 24 Parganas have been reported to be sulphur deficient [4]. A considerable area of West Bengal is sulphur deficient or likely to become deficient except for the coastal and saline soils [1].

Only 54.7% of the geographical areas under red and lateritic soils in West Bengal have been brought under cultivation and rainy season rice is the major crop occupying about 75% of the gross cropped area. Farmers grow oilseeds in upland soils of the red and lateritic soils of West Bengal. Sulphur requirement of oilseed crops are more than cereals.

Beneficial effect of sulphur application on increasing yield of several oilseed, cereals, pulses and cash crops has been reported in sulphur deficient soils by several workers. [1, 8, 12]. The performance of various sulphur sources like gypsum (14–16% S), phosphogypsum (14-16%S), ammonium sulphate (24%S), single super phosphate (12%S), pyrites (22-24S%) and elemental sulphur (85-100%S) has been review by Sakal and Singh [1].

.Single superphosphate refers to the material obtained by treating phosphate rock with sulphuric or phosphoric acid or both. It is a multi-nutrient fetiliser containing 7% P, 12% S and 21% Ca. Single superphosphate accounts for about half of total S added through important fertilizers in India [8]. Even though on elemental basis, there is more S than P in single superphosphate, the product is rarely recognized for its S content. There is thus a strong need for detailed studies in this direction.

Elemental S–based products are the most concentrated source of S (85 – 100%S). Upon addition to the soil, elemental S has to be oxidized to yield the SO_4 from that can be absorbed by plants. This oxidation is accomplished by soil bacteria. The rate of oxidation depends upon the particle size of S, its degree of contact with soil, temperature, moisture, and aeration. In order to allow adequate time for transformation, it is applied 3 – 4 weeks ahead of planting the crop. In the acute shortage of edible oils for human diet in the country, sulphur can play key role in augmenting the production of oilseeds. Since India is a net importer of sulphur for manufacturing some of the important nitrogenous, phosphatic and potassic fertilisers. Therefore, alternative sulphur supply strategies must emphasize the use of indigenous sources of sulphur, the most dependable and cheaper such as pyrites and phosphogypsum.

Pyrites (FeS_2) is a mineral containing iron and sulphur (22 – 24%). Extensive deposits of sedimentary iron pyrites exist near Amjhore in Bihar, India [9]. In contrast to elemental S which oxidizes in the soil to produce sulphuric acid mainly through *Thiobacillus thiooxidans* bacteria, oxidation of pyrite in soil initially is brought about primarily through chemical action and microbial agents like *Thiobacillus ferroxidans* may be playing a minor role. Pyrites, a slow-release source of S is likely to prove a relatively better source of S in mitigating the increasing deficiency of S in intensively cropped soils [10]. On the other hand, phosphogypsum (16% S, 21% Ca and 0.2 – 1.2% P_2O_5) is the byproduct gypsum obtained during the manufacture of wet process phosphoric acid. Phosphogypsum can thus serve as the source of sulphur and calcium for plant growth like mineral gypsum. Less than 10% of the phosphogypsum is being used for agricultural purposes [11].

Only recently, magnesium sulphate has been included in the Fertiliser Control Order and given due recognition as a fertilizer. Magnesium sulphate, which is produced and used most commonly in India, is the Epsom salt, $MgSO_4$. $7H_2O$ containing 16% MgO and 13% S. Generally, it is selected for application in situations where Mg application also is required, as is case with several horticultural, plantation and field crops in Mg-deficient soils [12].

An attempt was taken to examine critically the indigenous sources of sulphur vis-a-vis other sulphur sources on yield and quality characters of rapeseed (*Brassica juncea* L.) hopefully could contribute to future sulphur management strategies in these soils.

MATERIALS AND METHODS

A field experiment was conducted at Agricultural Research Farm, Institute of Agriculture, Visva –Bharati University, Sriniketan ($23^0 03^/$N and $87^0 04^/$ E), West Bengal, India with rapeseed (*Brassica juncea* L. variety B9) during *winter* seasons of 2000-2001 and 2001-2002 to evaluate the effects of different sources and levels of S on the yield, uptake of S, oil content, oil yield of rapeseed and availability of S in soil. The experiment was conducted on a typical lateritic soil (Typic ochraqualf) of order Alfisol.

Half dose of nitrogen (40 kg ha^{-1}) and full dose of phosphorus (80 kg P_2O_5 ha^{-1}) and potassium (40 kg K_2O ha^{-1}) was applied as basal and remaining half dose of nitrogen (40 kg ha^{-1}) was applied after the first irrigation. The recommended doses of nitrogen, phosphorus and potash were applied as urea, triple superphosphate and muriate of potash, respectively. SSP was used as a source of S and its phosphorus content was also considered and adjusted with triple superphosphate as per treatments. Pyrite and elemental S were applied 15 days prior to sowing to facilitate oxidation of S in it whereas phosphogypsum and SSP were applied at the time of sowing. Rapeseed was sown in rows 15 cm apart maintaining 10 cm plant-to-plant distance. Recommended package of practices were followed to raise a good crop. After harvesting, yields of grain, stover and total dry matter, oil content of grains, oil yield, and protein content in grains were recorded.

Soil properties were determined following standard procedures. Available sulfur in the soil was extracted using 0.15% $CaCl_2$ solution [13]. The total sulphur in the soil was extracted by perchloric acid ($HClO_4$) digestion [14]. Sulfur content in the digest of plant and soil extract was determined using turbidimetric method of Chesnin and Yien [15]. The major soil properties of the plot used for the year 2000-2001 and 2001 – 2002 are presented in Table 1. Nuclear magnetic resonance (NMR) technique was used to estimate the oil content in grain [16].

Sulfur content in stover and grain sample was determined after wet digestion in diacid mixture (HNO_3 : $HClO_4$: : 4 : 1) as per Jackson [17](1973). Sulfur content in the digest of plant extract was determined using turbidimetric method of Chesnin and Yien [15]. Crude protein in rapeseed grain was determined by A.O.A.C. method [18]. Nuclear magnetic resonance (NMR) technique was used to estimate the oil content in grain [16].

Table 1: Some soil properties of the experimental plots prior to field experimentation

Soil properties	2000 - 2001	2001 -2002
pH (1: 2)	5.1	5.4
organic C (g kg^{-1})	4.5	4.1
CEC (Cmol (p^+) kg^{-1})	6.4	5.9
Available P (kg ha^{-1})	9.4	7.9
Available K (kg ha^{-1})	201,	226
Available S (kg ha^{-1})	20.1	20.6
Total S (kg ha^{-1})	641.5	506.0

The experiment was laid out in a Randomized Block Design (RBD) with treatments comprised of four sources of sulphur viz. pyrite, elemental S, phosphogypsum and SSP and five levels (0, 15, 30, 45 and 60 kg S ha^{-1}) and were replicated thrice. The collected data were analyzed statistically by using analysis of variance (ANOVA) technique with the help of computer package MSTAT – C and the significance differences were distinguished by the Fisher-LSD test at $p<0.05$.

RESULTS AND DISCUSSION

Grain, Stover and Total yield

Significant response of mustard due to the application of S fertilizers irrespective of S sources as evidenced by grain, straw and total dry matter yield was noted during 2000-2001 and 2001-2002 (Table 2). The grain yield of mustard ranged from 10.76 to 16.39 q ha^{-1} and 11.16 to 17.15 q ha^{-1} during 2000-2001 and 2001-2002, respectively.

Though the increase in grain yield was significant in S treated plots over control but higher S level i.e. 60 kg S ha^{-1} failed to register higher yield increase over that at 45 kg S ha^{-1}. Grain yield of mustard increased significantly with increased levels of S up to 45 kg S ha^{-1}, above which decreasing trend was observed except elemental S.

Single superphosphate was the best source of sulphur in increasing grain yield. However, single superphosphate, phosphogypsum and pyrites were *at par* with respect to grain, stover and total dry matter yield. The maximum grain yield (16.39 and 17.15 q ha^{-1}) was obtained with single superphosphate @ 45 kg S ha^{-1} during both the years. It is interesting to note that application of single superphosphate @ 30 and 45 kg S ha^{-1} level recorded significant increase in grain yield over respective levels of S as elemental S during both the years. Similarly phosphogypsum @ 30 kg S ha^{-1} yielded significant increase in grain yield over elemental S @ 30 kg S ha^{-1} during both the years.

Table 2. Effect of different sources and levels of S on grain and straw yield of rapeseed

S Sources	S (kg ha^{-1})	2000 - 2001			2001 – 2002		
		Grain	Straw	Total dry matter	Grain	Straw	Total dry matter
		……………..q ha^{-1}……………					
Pyrites	15	13.31	30.55	43.86	13.95	32.33	46.17
Elemental S	15	12.80	29.79	42.59	13.45	31.53	44.98
Single superphosphate	15	14.12	32.36	46.48	14.90	33.05	47.95
Phosphogypsum	15	13.75	31.60	45.35	14.21	32.74	46.95
Pyrites	30	14.86	32.03	46.89	15.08	34.63	49.71
Elemental S	30	13.46	32.83	46.29	14.31	31.90	46.21
Single superphosphate	30	15.40	36.75	52.15	16.38	36.42	52.80
Phosphogypsum	30	15.11	34.82	49.93	15.97	35.11	51.08
Pyrites	45	15.23	35.77	51.00	16.12	35.28	51.40
Elemental S	45	14.37	33.87	48.24	15.03	33.90	48.93
Single superphosphate	45	16.39	39.50	55.72	17.15	37.66	54.81
Phosphogypsum	45	16.08	37.32	53.40	16.91	35.51	52.42
Pyrites	60	15.11	36.42	51.53	15.98	35.83	51.81
Elemental S	60	14.81	35.11	49.92	15.38	34.13	49.51
Single superphosphate	60	16.06	39.50	55.96	16.76	38.25	55.01
Phosphogypsum	60	15.96	38.24	54.20	16.65	37.93	54.58
Control	0	10.76	23.44	34.20	11.16	25.55	36.71
L.S.D. (p=0.05)	---	1.54	3.85	5.23	1.39	4.31	5.69

The stover yield of mustard ranged from 23.44 to 39.50 q ha^{-1} during 2000-2001 and 2001-2002, respectively. Among these sources, the maximum stover yield (39.50 and 38.25 q ha^{-1}) was obtained with single superphosphate at 60 kg S ha^{-1}. The stover and grain yield of mustard, however, continued to increase with increasing levels of sulphur, irrespective of its sources. The total dry matter (grain + stover) yield follows the similar trend as in case of grain and stover yield during both the years. The increase in yield due to application of sulphur may be due to better metabolism and increased efficiency of other nutrients. Earlier, Jaggi [19] and Ghosh *et al.* [20] also observed similar response to sulphur in the range of 20-60 kg S ha^{-1}. In coarse textured soils, SSP and gypsum have been reported to be superior to other sources in increasing the yield of oilseeds [21].

Sulphur concentration in grain and stover of mustard crop

S concentration in grain and stover of mustard increased significantly with increasing S levels up to 60 kg S ha^{-1}, irrespective of sources of S during both the years (Table 3). Results indicate that the crop responded to S application since soil was deficient in available S. S concentration in mustard grain and stover due to graded levels of S ranged from 0.69 to 0.89 and 0.18 to 0.36 per cent during 2000 – 2001 and 0.67 to 0.94 per cent and 0.19 to 0.35 per cent, respectively during 2001 – 2002. The maximum concentration of S in grain and stover was recorded in single superphosphate treatment followed by phosphogypsum and pyrites and the least with elemental S among the sources of S during both the years.

On elemental basis, single superphosphate contains more S (12 %) than phosphorus (7 %). It also contains 21 per cent Ca. In general, single superphosphate accounts for about half of total S added through important fertilisers. Since deficiencies of S in soils and crops are on the increase. It is therefore, high time to realize the importance of single superphosphate as a source of S for correcting these deficiencies.

For agricultural purposes, phosphogypsum may be regarded as mineral gypsum plus. It contains more lime (30 to 34% CaO) as against 23 –28% in mineral gypsum, more S (16-20%) against 13% in gypsum and 0.5 to 1.2% P_2O_5 almost half of which is believed to be water soluble [22]. Field experiments in India have shown distinct benefit of adding pyrites (FeS_2) as a source of S to cereals, pulses and oilseeds [23]. Ghosh *et al.* [20] reported an increase in S concentration of raya (*Brassica juncea*) along with the increase in doses of S. The higher concentration of S in mustard grain than stover clearly indicates the mobilization of S from plant parts to grain.

Sulphur uptake

Significant differences of the S sources and levels for S uptake by grain and stover over control were noticed (Table 4). The total S uptake continued to increase with the increase in levels of S irrespective of its source. The highest total S uptake was observed at all levels of S when SSP was the S source followed by phosphogypsum and pyrites, which was owing to the trend observed in grain and stover yield. Elemental S recorded the lowest uptake at its all levels. Total S uptake was, however, found to be highest in grain than stover of mustard. The highest total S uptake (28.51 and 29.13 kg ha^{-1}) was noticed with single superphosphate followed by phosphogypsum (25.95 and 28.92 kg ha^{-1}) and pyrites (24.92 and 26.32 kg ha^{-1}), respectively @ 60 kg S ha^{-1} during both the years. Among S sources the lowest total S uptake was recorded with elemental S with regards to single superphosphate, phosphogypsum and pyrites in all the corresponding levels during 2000 –2001 and 2001-2002. The uptake of S by mustard grain was higher than stover during both the years. This might be due to the mobilization of S from plant parts to grain. On the other hand, S containing amino acids viz. cystine, cysteine and methionine are the constituents of grain protein. Ghosh *et al.* [20] also reported higher S content and uptake by mustard with S application.

Table 3. Effect of sources and levels of S on S content (%) of rapeseed

S Sources	S levels (kg ha^{-1})	2000-2001		2001-2002	
		Grain	Straw	Grain	Straw
Pyrites	15	0.77	0.27	0.81	0.26
Elemental S	15	0.73	0.23	0.77	0.24
Single superphosphate	15	0.79	0.29	0.85	0.27
Phosphogypsum	15	0.79	0.27	0.84	0.27
Pyrites	30	0.78	0.29	0.85	0.29
Elemental S	30	0.75	0.25	0.79	0.26
Single superphosphate	30	0.82	0.33	0.90	0.30
Phosphogypsum	30	0.81	0.30	0.88	0.29
Pyrites	45	0.81	0.33	0.90	0.31
Elemental S	45	0.79	0.28	0.83	0.27
SSP	45	0.86	0.35	0.93	0.33
Phosphogypsum	45	0.84	0.31	0.91	0.32
Pyrites	60	0.83	0.34	0.93	0.32
Elemental S	60	0.80	0.30	0.86	0.29
Single superphosphate	60	0.89	0.36	0.94	0.35
Phosphogypsum	60	0.86	0.32	0.94	0.35
Control	0	0.69	0.18	0.67	0.19
L.S.D. (p=0.05)	---	0.12	0.03	0.09	0.03

Table 4. Effect of sources and levels of S on uptake of S (kg ha^{-1}) by rapeseed

S Sources	S levels (kg ha^{-1})	2000-2001			2001-2002		
		Grain	Straw	Total	Grain	Straw	Total
Pyrites	15	10.25	8.24	18.49	11.29	8.37	19.66
Elemental S	15	9.34	6.85	16.19	10.35	7.56	17.91
Single superphosphate	15	11.15	9.38	20.53	12.66	8.92	21.58
Phosphogypsum	15	10.86	8.53	19.39	11.93	8.83	20.76
Pyrites	30	11.59	9.28	20.87	12.81	10.04	22.85
Elemental S	30	10.09	8.20	18.29	11.30	8.29	19.59
Single superphosphate	30	12.62	12.12	24.74	14.74	10.92	25.66
Phosphogypsum	30	12.23	10.44	22.67	14.05	10.18	24.23
Pyrites	45	12.33	11.80	24.13	14.50	10.93	25.43
Elemental S	45	11.35	9.48	20.83	12.47	9.15	21.62
Single superphosphate	45	14.09	13.76	27.85	15.94	12.42	28.36
Phosphogypsum	45	13.50	11.56	25.06	15.38	11.36	26.94
Pyrites	60	12.54	12.38	24.92	14.86	11.46	26.32
Elemental S	60	11.84	10.53	22.37	13.22	9.89	23.11
Single superphosphate	60	14.29	14.22	28.51	15.75	13.38	29.13
Phosphogypsum	60	13.72	12.23	25.95	15.65	13.27	28.92
Control	0	7.42	4.21	11.63	7.47	4.85	12.32
L.S.D. (p=0.05)	---	1.87	1.68	3.67	1.64	1.74	2.76

Oil content and oil yield

The significant increase of oil content and oil yield over control was recorded irrespective of levels and sources of S during both the years (Table 5). The oil content in mustard grain increased with increasing levels of S up to 30 kg S ha^{-1} with single superphosphate, phosphogypsum and pyrites and thereafter decreasing trend was observed. However, the increase in oil content up to 60 kg S ha^{-1} was observed with elemental S. The highest oil content (42.40 and 43.13 %) was observed in case of single superphosphate followed by phosphogypsum (42.23 and 42.99 %) and pyrites (41.95 and 42.84 %) as source of S @ 30 kg S ha^{-1} during 2000-2001 and 2001-2002, respectively. Among the sulphur sources, the lowest oil content was recorded in case of elemental S as source of S in all its corresponding levels. However the highest oil yield (6.93 and 7.37 q ha^{-1}) was obtained at the application of 45 kg S ha^{-1} with single superphosphate followed by phosphogypsum (6.78 and 7.25 q ha^{-1}) and pyrites (6.37 and 6.89 q ha^{-1}) during both the years. The decreasing trend of oil content due to higher levels of S might be due to the dilution effect of increased seed yield. Among the S sources, the lowest oil yield was recorded at all the levels of S when elemental S was the source of S. The lowest oil yield in elemental S treated plots may be due to comparatively less grain yield and oil content as compared to other S sources.

The superiority of single superphosphate and phosphogypsum over pyrites and elemental S with regards to oil content and oil yield might be due to higher solubility of single superphosphate and phosphogypsum resulting in easily available forms of S. S plays the role in formation of glucosides, which on hydrolysis produce higher amount of oil as well as allylisothiocyanate, which are responsible for pungency, a determinative factor of oil quality [24]. Ghosh *et al*. [20] and Jaggi [19] also reported the highest oil yield by the application of S in the range of 45-50 kg ha^{-1} in mustard crop.

Table 5. Effect of sources and levels of S on oil content, oil yield and protein content of rapeseed

S sources	S levels (kg ha^{-1})	Oil content (%)		Oil yield (q ha^{-1})		Protein content (%)	
		2000-2001	2001-2002	2000-2001	2000-2001	2000-2001	2001-2002
Pyrites	15	41.59	42.69	19.73	19.73	19.73	19.76
Elemental S	15	41.27	42.09	19.37	19.37	19.37	19.55
Single superphosphate	15	41.71	42.97	19.92	19.92	19.92	19.99
Phosphogypsum	15	41.60	42.87	19.85	19.85	19.85	19.89
Pyrites	30	41.95	42.84	19.97	19.97	19.97	19.91
Elemental S	30	41.56	42.24	19.56	19.56	19.56	19.81
Single superphosphate	30	42.40	43.13	20.61	20.61	20.61	20.70
Phosphogypsum	30	42.23	42.99	20.30	20.30	20.30	20.51
Pyrites	45	41.89	42.75	21.50	21.50	21.50	20.95
Elemental S	45	41.62	42.36	19.89	19.89	19.89	20.13
Single superphosphate	45	42.31	43.01	21.66	21.66	21.66	21.35
Phosphogypsum	45	42.19	42.90	21.53	21.53	21.53	21.06
Pyrites	60	41.70	42.70	21.71	21.71	21.71	21.89
Elemental S	60	41.67	42.44	20.01	20.01	20.01	20.57
Single superphosphate	60	42.19	42.98	21.92	21.92	21.92	22.22
Phosphogypsum	60	42.07	42.86	21.80	21.80	21.80	21.92
Control	0	38.62	40.50	19.11	19.11	19.11	19.27
L.S.D. (p=0.05)	---	1.28	0.99	0.40	0.40	0.40	0.36

Protein content

Results revealed significant effect of S on the protein content in mustard. The protein content of mustard grain increased with increasing levels of S irrespective of S source during 2000-2001 and 2001-2001 (Table 5). Progressively significant increase in protein content of mustard seed was observed with each S level up to 60 kg S ha^{-1}. The highest protein content (21.92 and 22.22%) was observed in case of single superphosphate followed by phosphogypsum (21.80 and 21.92%), pyrites (21.71 and 21.89%) and elemental S (20.01 and 20.57%) as source of S @ 60 kg S ha^{-1} during 2000-2001 and 2001-2002, respectively. Adequate supply of S to rapeseed mustard crops promotes the synthesis of S containing amino acids and proteins. Jaggi [19] also observed increase in protein content in mustard with sulphur.

Apparent sulphur recovery and response by mustard

Significant amount of applied S was recovered by the mustard crop, which ranged from 17.90 to 59.33% and 17.98 to 61.72% during 2000-2001 and 2001-2002, respectively (Table 6). Among the sources, S recovery and crop response was more with single superphosphate followed by phosphogypsum and pyrites, whereas the lowest recovery of S was with elemental S. It was interesting to note that the recovery of S was higher at lower levels of S application, which decreases with increasing S levels irrespective of S sources. Crop response in terms of kg grain per kg S ranged from 6.75 to 22.40 and 7.03 to 24.93 during 2000-2001 and 2001-2002, respectively (Table 5).

Among the S sources, crop response was more with single superphosphate followed by phosphogypsum, pyrites and elemental S at all the corresponding levels under consideration. The greater recovery of S with lower levels of added S in mustard crop was noticed during both the years. Ghosh *et al.* [20] also reported the higher recovery of S with lower levels of added S in mustard crop. Although, the percent recovery of S was higher at lower application rate, the absolute uptake of added S increased with increasing rate of application. A higher recovery is indicative of a more efficient uptake while higher yield is necessary for a more efficient utilization of the S taken up by the plants.

Available sulphur content in soil after mustard harvest

Available S content in soil varied from 9.2 to 13.1 mg kg^{-1} and 10.2 to 14.7 mg kg^{-1} after the harvest of mustard crop during 2000-2001 and 2001-2002, respectively (Table 7). Increase in available S content in soils, after harvest of mustard crop increased with increasing levels of S application from 0 to 60 kg S ha^{-1}. A significant increase in available S in soil was found over control from 30 kg S ha^{-1} onwards during 2000-2001, whereas significant increase in available S over control was observed with all the levels and sources of S during 2001-2002. Results indicate that graded levels and sources of S application not only increase the available S status over control, but also over initial soil S status. Balangoudar *et al.* [25] also reported that the available S content in soils increased with increase in S levels from 0 to 40 kg S ha^{-1} after the harvests of moong (*Vigna radiate* L.).

Table 6. Apparent S recovery and response of S as a result of application of graded levels and sources of S to rapeseed

S Sources	2000-2001				2001-2002			
	Levels of S (kg ha^{-1})				Levels of S (kg ha^{-1})			
	15	30	45	60	15	30	45	60
	Apparent S recovery (%)							
Pyrites	45.73	30.80	22.77	22.15	48.93	35.10	29.13	23.33
Elemental S	30.30	22.20	20.44	17.90	37.26	24.23	20.66	17.98
Single superphosphate	59.33	43.70	36.04	28.13	61.73	44.46	35.64	28.01
Phosphogypsum	51.73	36.80	29.84	23.86	56.26	39.70	32.48	27.66
	Response of S (kg grain kg^{-1} S)							
Pyrites	17.00	13.66	9.93	7.25	18.60	13.06	11.02	8.03
Elemental S	13.60	9.00	8.02	6.75	15.26	10.50	8.60	7.03
Single superphosphate	22.40	15.46	12.51	8.83	24.93	17.40	13.31	9.33
Phosphogypsum	19.93	14.50	11.82	8.66	20.33	16.03	12.77	9.15

Changes of pH in soils after mustard harvest

The data on changes in soil pH as a result of application of graded levels and sources of S after the harvest of mustard crop are presented in Table 7.The results clearly show that all the sources of S have acidifying effect on soil pH indicating the need of liming along with the application of S to soils which not only neutralizes the soil acidity but favours S availability. In general the rate of S oxidation in acid soils increases with increasing soil pH. Calcium carbonate additions to soils helps in increase the rate of sulphur oxidation and mineralization of organic S in soils [26].

CONCLUSION

Field experiments revealed that sources and levels of S have significant influence on grain yield, total biological yield, S content in grain and stover, total S uptake, oil yield and protein content of rapeseed crop in lateritic soils of the region. Over all best performance was observed when S was applied @ 45 kg S ha^{-1}, except elemental S, which requires higher dose. Among the S sources the best performance was observed with single superphosphate followed by phosphogypsum, pyrites and elemental S.

Table 7. Changes in available sulphur and soil reaction (pH) as a result of application of graded levels and sources of S to rapeseed

Sources of S	2000-2001					2001-2002					2000-2001					2001-2002				
	15	30	45	60	Mean	15	30	45	60	Mean	15	30	45	60	Mean	15	30	45	60	Mean
	Available S					Available S					pH					pH				
Pyrites	9.2	10.4	12.0	12.9	11.1	10.3	11.9	13.2	14.4	12.4	4.91	4.90	4.89	4.53	4.80	5.09	4.75	4.88	4.86	4.89
Elemental S	9.3	10.2	11.8	12.1	10.8	10.7	12.0	13.6	14.7	12.7	4.53	4.65	4.67	4.39	4.56	4.70	5.03	4.58	4.99	4.82
Single superphosphate	9.7	10.9	12.6	12.9	11.5	10.4	11.9	13.1	14.1	12.3	4.80	5.35	4.79	5.09	5.00	4.86	4.84	4.77	4.96	4.85
Phosphogypsum	9.6	10.8	12.7	13.1	11.5	10.2	12.1	13.0	14.5	12.4	4.90	5.00	5.63	5.28	5.20	4.61	5.05	5.01	5.05	4.93
Mean	9.4	10.5	12.2	12.7	----	10.4	11.9	13.2	14.4	----	4.78	4.97	4.99	4.82	---	4.81	4.91	4.81	4.96	----
Control	8.8					8.6					5.43					5.23				
Initial	9.0					9.2					5.11					5.4				
L.S.D. (p=0.05)	1.36					1.27					0.619					0.358				

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