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Nutrient uptake and economics of maize (*Zea mays* L.) production as influenced by sulphur sources and levels in a calcareous *Vertisol*

Shrinivas Babu Ramanayak[1*], Anand Naik[2], Siddaram[3], Shreenivas B V[4], M A Bellaki[5]
[1] Department of Soil Science, College of Agriculture, Raichur, UAS, Raichur, Karnataka, India
[2] Associate Professor, Senior Farm Superintendent, Soil Science, University of Agricultural Sciences, Raichur, Karnataka, India
[3] Assistant Professor, Agronomy, University of Agricultural Sciences, Raichur, Karnataka, India
[4] Soil Scientist, Soil science, ICAR-KVK Kalaburagi-1, Karnataka, India
[5] Professor, Soil Science, University of Agricultural Sciences, Raichuir, Karnataka, India
Corresponding Author: Shrinivas Babu Ramanayak
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Abstract
A split-plot field experiment was conducted in *kharif* 2025 at ICAR-KVK, Kalaburagi-II, Karnataka, to determine how three sulphur sources (gypsum, bentonite sulphur, elemental sulphur) and four levels (0, 10, 20, 30 kg S ha^{-1}) influence N, P, K and S uptake and the economics of maize (*Zea mays* L.) hybrid RCRMH-2) on a sulphur-deficient calcareous *Vertisol*. Bentonite sulphur gave significantly higher total N uptake (104.69 kg ha^{-1}) than gypsum (80.88), with elemental sulphur intermediate (91.32) P, K and S uptake followed the same order. Uptake of all four nutrients increased significantly with sulphur level, peaking at 30 kg S ha^{-1} (N 122.63, P 33.75, K 128.89, S 20.19 kg ha^{-1}) and falling to about 43-60 per cent of these values in the control. The interaction was non-significant except for K uptake in straw and total. Bentonite sulphur at 30 kg S ha^{-1} (S_2L_3) gave the highest uptake of every nutrient (137.25 N, 37.80 P, 146.93 K, 23.21 S kg ha^{-1}), while gypsum with no sulphur (S_1L_4) gave the lowest (47.78, 11.66, 30.05, 7.24). Bentonite sulphur recorded the highest net profit (₹1,05,048 ha^{-1}) and benefit:cost ratio (2.60) among sources, and 30 kg S ha^{-1} among levels (₹1,15,325 ha^{-1}, 2.72), against ₹55,965 ha^{-1} and 1.74 in the control. The best combination, bentonite sulphur at 30 kg S ha^{-1}, returned ₹1,70,000 gross, ₹1,27,298 net and a B:C ratio of 3.98. It is therefore recommended as the most nutrient-efficient and remunerative practice for maize on calcareous *Vertisols.*

Keywords: Maize, sulphur sources, nutrient uptake, benefit:cost ratio, calcareous *Vertisol*

Introduction

Balanced nutrition is central to realising the genetic yield potential of maize (*Zea mays* L.), and while nitrogen, phosphorus and potassium remain the pillars of most fertiliser schedules, sulphur has emerged as an equally critical nutrient because it governs the assimilation of absorbed nitrogen into protein and influences the uptake of several other macro- and micronutrients. In calcareous *Vertisols* such as those of the Kalaburagi region of Karnataka, high free calcium carbonate content, alkaline reaction and low organic matter combine to restrict sulphur availability, and the resulting imbalance in the nitrogen-to-sulphur ratio can depress the efficiency with which applied fertilisers are converted into nutrient uptake and, ultimately, into economic yield.

Because sulphur sources differ substantially in their rate of sulphate release – gypsum being rapidly soluble and prone to leaching, bentonite sulphur releasing sulphate gradually through microbial oxidation, and elemental sulphur oxidising still more slowly - the quantity of nitrogen, phosphorus, potassium and sulphur actually taken up by the crop, and the return on the fertiliser investment, would be expected to vary correspondingly. A source that sustains sulphate supply through the season could be expected not only to raise nutrient uptake through improved root growth and rhizosphere conditions but also to translate this improvement into a more favourable cost-benefit outcome, since the additional expenditure on a costlier sulphur source is worthwhile only if it is compensated by proportionately higher returns. Similar source-dependent gains in nutrient uptake and profitability have been documented in other *Vertisol*-grown, sulphur-responsive crops: Meena and Meena (2015) [9] recorded significantly higher N, P and S uptake and the highest net return and benefit:cost ratio under bentonite sulphur relative to gypsum and elemental sulphur in Indian mustard on Rajasthan *Vertisols*, while parallel thesis work on maize itself by Siddique (2007) and Varavipour (1993) [17, 20] similarly linked sulphur source and level to both nutrient uptake and the profitability of the crop. This investigation was therefore undertaken to quantify the effect of gypsum, bentonite sulphur and elemental sulphur, applied at graded levels, on the uptake of nitrogen, phosphorus, potassium and sulphur by maize and on the resultant cost of cultivation, returns and benefit:cost ratio, so as to identify the most nutrient-efficient and economically viable sulphur management option for maize on calcareous *Vertisols*.

Materials and Methods

1. Site, soil and treatments

The trial was conducted during *kharif* 2025 at ICAR-Krishi Vigyan Kendra, Kalaburagi-II (Raddewadgi), Karnataka (17° 33' N, 76° 83' E; 550 m amsl) in a calcareous clay soil (pH 8.45, EC 0.35 dS m^{-1}, organic carbon 4.30 g kg^{-1}, available S 9.13 mg kg^{-1}), following a split-plot design with twelve treatments replicated thrice. Three sulphur sources – gypsum (S1), bentonite sulphur (S_2) and elemental sulphur (S_3) -formed the main plots, and four sulphur levels – 10

(L_1), 20 (L_2), 30 (L_3) and 0 kg S ha $^{-1}$ (L_4, control) - formed the sub-plots. Maize hybrid RCRMH-2 was sown on 22 July 2025 at 60 × 20 cm spacing and harvested on 11 November 2025, with a uniform basal application of 150:65:65 kg N: P2O5: K2O ha $^{-1}$ and 10 t FYM ha $^{-1}$ to all except the absolute control, and the required quantity of each sulphur source thoroughly incorporated at sowing.

2. Plant analysis and nutrient uptake

Oven-dried grain and straw samples were digested with a di-acid mixture (HNO_3: $HClO_4$, 10: 4) after overnight pre-digestion with concentrated HNO_3. Total nitrogen was determined by the Kjeldahl method, phosphorus colorimetrically by the vanadomolybdate yellow-colour method, potassium by flame photometry and sulphur turbidimetrically as barium sulphate, all following Jackson (1973) and Page *et al*. (1982) [7, 12]. Nutrient uptake in grain and straw was calculated by multiplying nutrient content (%) by the respective dry-matter yield, and total uptake obtained as the sum of grain and straw uptake, expressed in kg ha $^{-1}$.

3. Economic analysis

The cost of cultivation for each treatment was worked out from the prevailing prices of inputs (seed, fertilisers including the sulphur sources, plant protection chemicals) and labour charges for all field operations. Gross returns were calculated by multiplying the grain and stalk yield of each treatment by the prevailing market price at harvest, and net returns were obtained by subtracting the cost of cultivation from the gross returns. The benefit:cost ratio was computed as gross returns divided by the cost of cultivation.

4. Statistical analysis

The data were analysed following Fisher's method of analysis of variance for a split-plot design (Gomez and Gomez, 1984) [6], with treatment means compared using the critical difference (CD) at $P = 0.05$, non-significant effects are denoted "NS" in the tables. For every character, the source × level combination giving the numerically highest and lowest value is additionally identified below the interaction row of each table, even where the interaction itself was statistically non-significant.

Results and Discussion

1. Nitrogen content and uptake

Nitrogen content in both grain and straw, and consequently nitrogen uptake, were significantly higher under bentonite sulphur (S_2) than under gypsum (S_1), with elemental sulphur (S_3) intermediate; all three sources differed significantly from one another (Table 1). Total nitrogen uptake reached 104.69 kg ha $^{-1}$ under S_2 against 80.88 kg ha $^{-1}$ under S_1. Among levels, uptake rose significantly and progressively up to 30 kg S ha-1 (L_3, total uptake 122.63 kg ha $^{-1}$), roughly 132 per cent above the control L_4 (52.89 kg ha $^{-1}$). The source × level interaction was non-significant, with S_2L_3 recording the highest total nitrogen uptake (137.25 kg ha $^{-1}$) and S_1L_4 the lowest (47.78 kg ha $^{-1}$).

Sulphur and nitrogen metabolism are closely linked because sulphur is a constituent of cysteine and methionine and supports nitrate reductase activity; an assured sulphur supply from bentonite sulphur's slow oxidation therefore facilitated more efficient conversion of absorbed nitrate into protein, in addition to promoting greater root growth and biomass that raised total nitrogen absorption. These results agree with the improved nitrogen uptake and nitrogen use efficiency under adequate sulphur nutrition reported by Salvagiotti *et al*. (2009) [16], and with the significantly higher N uptake recorded under bentonite sulphur than gypsum in mustard by Meena and Meena (2015) [9].

Table 1: Nitrogen content and uptake by maize at harvest as influenced by sulphur sources and levels

Treatment	N (%) Grain	N (%) Straw	N uptake Grain (kg ha $^{-1}$)	N uptake Straw (kg ha $^{-1}$)	N uptake Total (kg ha $^{-1}$)
S_1: Gypsum	1.27	0.45	53.98	26.26	80.88
S_2: Bentonite sulphur	1.37	0.53	68.50	35.57	104.69
S_3: Elemental sulphur	1.31	0.48	60.58	30.10	91.32
S.Em±	0.02	0.01	0.95	0.66	1.52
CD @ 5%	0.07	0.04	3.73	2.57	5.95
L_1: 10 kg S ha $^{-1}$	1.24	0.43	61.16	27.55	88.98
L_2: 20 kg S ha $^{-1}$	1.36	0.52	69.84	34.82	104.66
L_3: 30 kg S ha $^{-1}$	1.46	0.61	79.78	42.85	122.63
L_4: 0 kg S ha $^{-1}$ (Control)	1.20	0.37	35.54	17.35	52.89
S.Em±	0.03	0.01	1.44	0.94	2.43
CD @ 5%	0.09	0.04	4.27	2.78	7.23
S × L interaction	NS	NS	NS	NS	NS
Highest (S_2L_3)	1.50	0.65	88.50	48.75	137.25
Lowest (S_1L_4)	1.16	0.34	32.48	15.30	47.78

2. Phosphorus content and uptake

Phosphorus content and uptake mirrored the nitrogen pattern: content in grain and straw was highest under S2 (0.40 and 0.12 per cent) and lowest under S1 (0.36 and 0.09 per cent), and total phosphorus uptake was significantly higher under S2 (28.31 kg ha-1) than S1 (21.18 kg ha-1), with S3 intermediate (24.45 kg ha-1) (Table 2). Sulphur level had an even sharper effect, total uptake rising from 13.48 kg ha-1 under the control L4 to 33.75 kg ha-1 under L3, an increase of about 150 per cent. The source × level interaction was non-significant, with S2L3 giving the highest total phosphorus uptake (37.80 kg ha-1) and S1L4 the lowest (11.66 kg ha-1).

Localised acidification generated during the oxidation of bentonite and elemental sulphur granules would have increased native phosphorus solubility in this calcium-carbonate-rich soil, in addition to the greater root surface area and biomass associated with improved sulphur nutrition, both of which favour higher phosphorus absorption. Nanthakumar and Panneerselvam (2017) [10]

similarly reported that sulphur application increased phosphorus availability and uptake in maize through enhanced phosphorus release from soil, a pattern also reflected in the significantly higher P uptake recorded under bentonite sulphur in mustard by Meena and Meena (2015) [9].

Table 2: Phosphorus content and uptake by maize at harvest as influenced by sulphur sources and levels

Treatment	P (%) Grain	P (%) Straw	P uptake Grain (kg ha $^{-1}$)	P uptake Straw (kg ha $^{-1}$)	P uptake Total (kg ha $^{-1}$)
S1: Gypsum	0.36	0.09	15.66	5.52	21.18
S2: Bentonite sulphur	0.40	0.12	20.09	8.22	28.31
S3: Elemental sulphur	0.38	0.11	17.79	6.66	24.45
S.Em±	0.01	0.00	0.42	0.27	0.48
CD @ 5%	0.02	0.01	1.66	1.08	1.87
L1: 10 kg S ha-1	0.35	0.09	17.30	5.73	23.03
L2: 20 kg S ha-1	0.39	0.12	20.27	8.06	28.33
L3: 30 kg S ha-1	0.44	0.14	23.92	9.83	33.75
L4: 0 kg S ha-1 (Control)	0.33	0.08	9.90	3.57	13.48
S.Em±	0.01	0.00	0.66	0.33	0.70
CD @ 5%	0.03	0.01	1.95	0.98	2.03
S × L interaction	NS	NS	NS	NS	NS
Highest (S2L3)	0.45	0.15	26.55	11.25	37.80
Lowest (S1L4)	0.32	0.06	8.96	2.70	11.66

3. Potassium content and uptake

Potassium content and uptake were also significantly higher under S2 than S1 in both grain and straw, with total potassium uptake of 107.31 kg ha $^{-1}$ under S2 against 70.08 kg ha $^{-1}$ under S1 (Table 3). The source × level interaction, non-significant for grain potassium content and grain uptake, was significant for straw potassium content (CD = 0.19) and for straw and total potassium uptake (CD = 9.15 and 8.11 kg ha $^{-1}$, respectively): the highest total uptake was recorded under S2L3 (146.93 kg ha-1) and the lowest under S1L4 (30.05 kg ha $^{-1}$). Among levels, total uptake rose from 47.86 kg ha $^{-1}$ under L4 to 128.89 kg ha $^{-1}$ under L3.

The continuous sulphate supply from bentonite sulphur appears to have improved root membrane permeability and physiological efficiency, favouring greater potassium absorption and translocation, in addition to the larger crop biomass produced under this treatment. Bharathi and Poongothai (2008a) similarly reported significantly higher potassium uptake in grain and stover of maize with increasing sulphur levels.

Table 3: Potassium content and uptake by maize at harvest as influenced by sulphur sources and levels

Treatment	K (%) Grain	K (%) Straw	K uptake Grain (kg ha-1)	K uptake Straw (kg ha $^{-1}$)	K uptake Total (kg ha $^{-1}$)
S1: Gypsum	0.40	0.88	17.29	52.79	70.08
S2: Bentonite sulphur	0.46	1.28	23.32	83.99	107.31
S3: Elemental sulphur	0.43	0.97	20.09	62.45	82.54
S.Em±	0.01	0.02	0.38	1.46	1.25
CD @ 5%	0.04	0.09	1.50	5.74	4.91
L1: 10 kg S ha-1	0.39	0.82	19.45	51.98	71.43
L2: 20 kg S ha-1	0.45	1.12	23.22	75.16	98.38
L3: 30 kg S ha-1	0.49	1.45	27.06	101.83	128.89
L4: 0 kg S ha-1 (Control)	0.38	0.78	11.21	36.66	47.86
S.Em±	0.01	0.04	0.57	1.78	1.58
CD @ 5%	0.04	0.11	1.69	5.29	4.68
S × L interaction	NS	0.19	NS	9.15	8.11
Highest (S2L3)	0.52	1.55	30.68	116.25	146.93
Lowest (S1L4)	0.35	0.45	9.80	20.25	30.05

CD values in the S × L interaction row for straw content, straw uptake and total uptake are the least significant differences for comparing individual treatment-combination means; grain content and grain uptake interactions were non-significant (NS).

4. Sulphur content and uptake

Sulphur content in grain and straw, and total sulphur uptake, were all significantly higher under S_2 (17.41 kg ha $^{-1}$) than S_1 (12.26 kg ha $^{-1}$), with S_3 intermediate (14.92 kg ha $^{-1}$) (Table 4). Uptake rose sharply with level, from 8.77 kg ha $^{-1}$ under the control L_4 to 20.19 kg ha $^{-1}$ under L_3, more than double. The source × level interaction was non-significant, with S_2L_3 recording the highest total sulphur uptake (23.21 kg ha $^{-1}$) and S_1L_4 the lowest (7.24 kg ha $^{-1}$).

The slow and sustained oxidation of bentonite sulphur ensured a more continuous supply of sulphate for assimilation into sulphur-containing amino acids and coenzymes across the crop cycle, a mechanism consistent with the increased sulphur uptake reported by Sakal *et al*. (2000), Dwivedi *et al*. (2002) and Bharathi *et al*. (2009) [3, 5, 15] with rising sulphur application.

Table 4: Sulphur content and uptake by maize at harvest as influenced by sulphur sources and levels

Treatment	S (%) Grain	S (%) Straw	S uptake Grain (kg ha $^{-1}$)	S uptake Straw (kg ha $^{-1}$)	S uptake Total (kg ha $^{-1}$)
S_1: Gypsum	0.15	0.10	6.37	5.89	12.26
S_2: Bentonite sulphur	0.17	0.13	8.59	8.82	17.41
S_3: Elemental sulphur	0.16	0.12	7.53	7.39	14.92

S.Em±	0.00	0.00	0.17	0.16	0.27
CD @ 5%	0.01	0.01	0.68	0.64	1.05
L_1: 10 kg S ha $^{-1}$	0.15	0.10	7.25	6.37	13.62
L_2: 20 kg S ha $^{-1}$	0.17	0.12	8.60	8.28	16.88
L_3: 30 kg S ha $^{-1}$	0.18	0.15	9.87	10.32	20.19
L_4: 0 kg S ha $^{-1}$ (Control)	0.14	0.10	4.27	4.50	8.77
S.Em±	0.00	0.00	0.26	0.21	0.43
CD @ 5%	0.01	0.01	0.77	0.63	1.29
S × L interaction	NS	NS	NS	NS	NS
Highest (S_2L_3)	0.19	0.16	11.21	12.00	23.21
Lowest (S_1L_4)	0.13	0.08	3.64	3.60	7.24

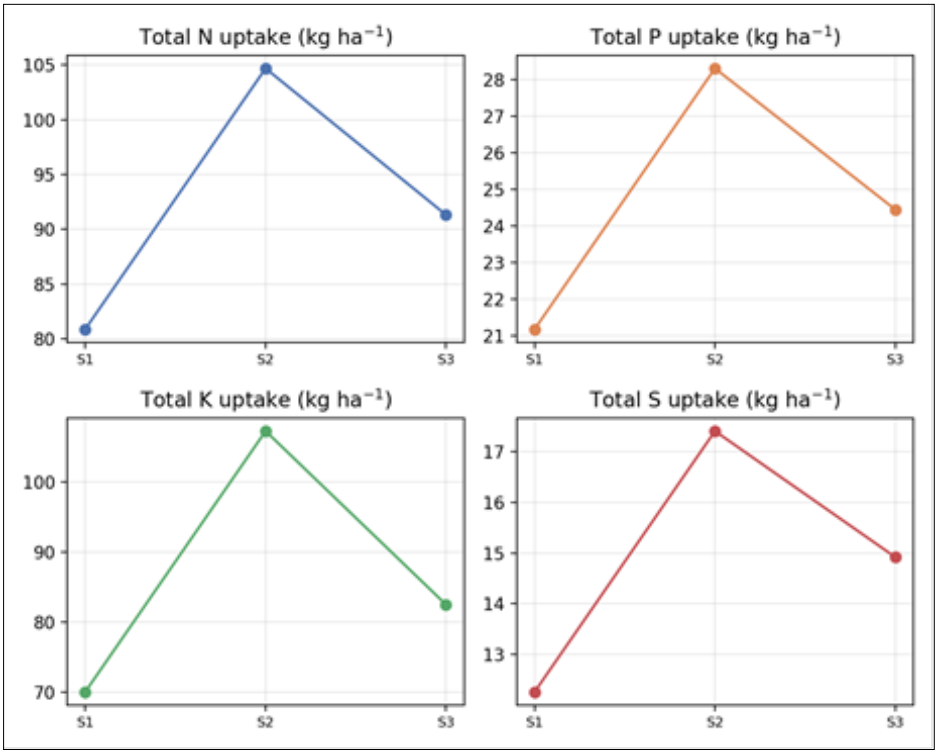


Fig 1: Total N, P, K and S uptake by maize as influenced by sulphur sources

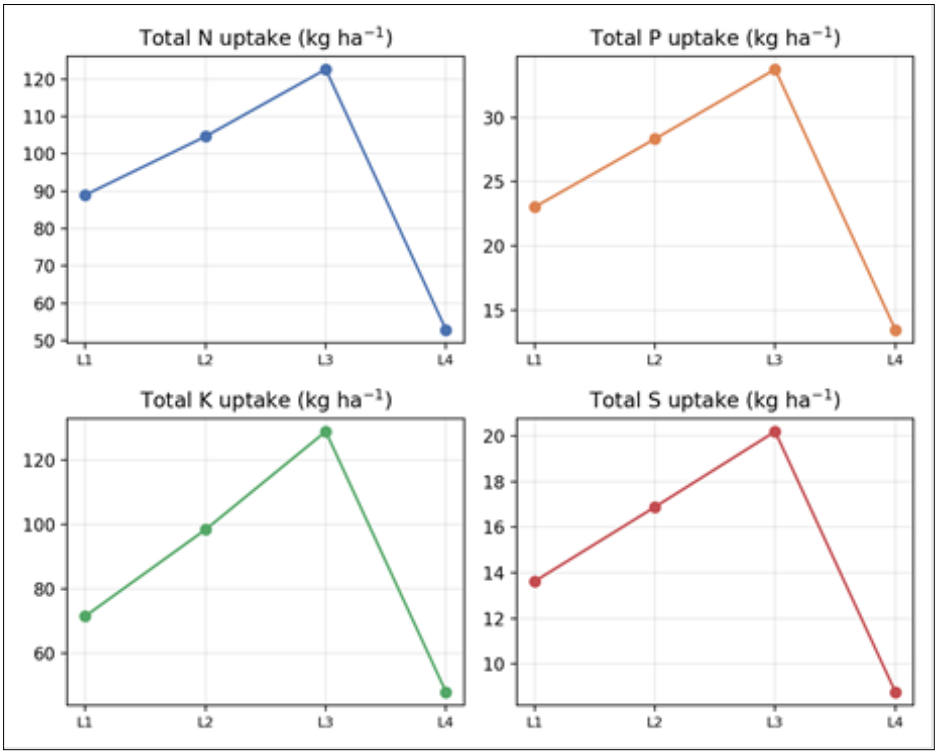


Fig 2: Total N, P, K and S uptake by maize as influenced by sulphur levels

5. Cost of cultivation

The cost of cultivation varied only with the cost of the sulphur source and the quantity applied, all other operations being uniform across treatments (Table 5). It was highest under S_3L_3 (₹ 43,002 ha-1) and S_2L_3 (₹ 42,702 ha $^{-1}$) and lowest, and identical, under the control treatments of all three sources (₹ 32,102 ha $^{-1}$), where no sulphur fertiliser was applied. Averaged across levels, the cost of cultivation rose only slightly from source to source, from ₹ 36,737 ha $^{-1}$ under S_1 to ₹ 39,677 ha $^{-1}$ under S_2 and ₹ 39,827 ha $^{-1}$ under S_3 (Fig. 3), and averaged across sources it rose from ₹ 41,582 ha $^{-1}$ under L_1 to ₹ 42,342 ha $^{-1}$ under L_3, an increase of less than 2 per cent, while the control L_4 was substantially cheaper (₹ 32,102 ha $^{-1}$) simply because no sulphur fertiliser was purchased (Fig. 4). This small increment in cost across both sources and levels, set against the much larger gains in yield and returns described below, underlines why bentonite sulphur and higher sulphur levels remained profitable despite the additional input expenditure, a pattern also highlighted by Rietra *et al*. (2017) [14] in their analysis of nutrient synergism and fertiliser-use efficiency.

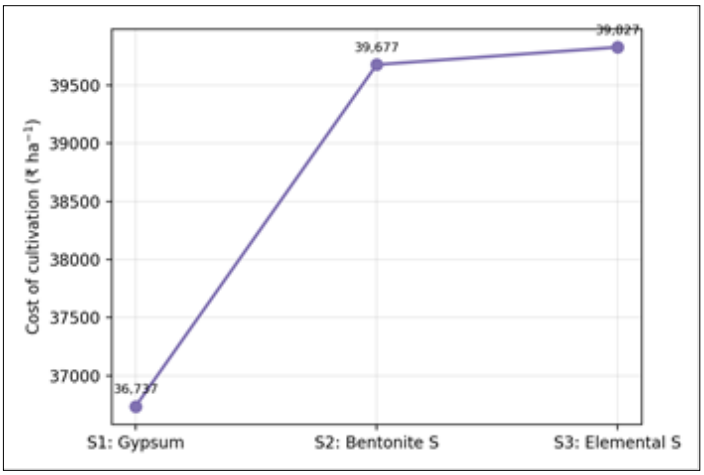


Fig 3: Cost of cultivation of maize as influenced by sulphur sources

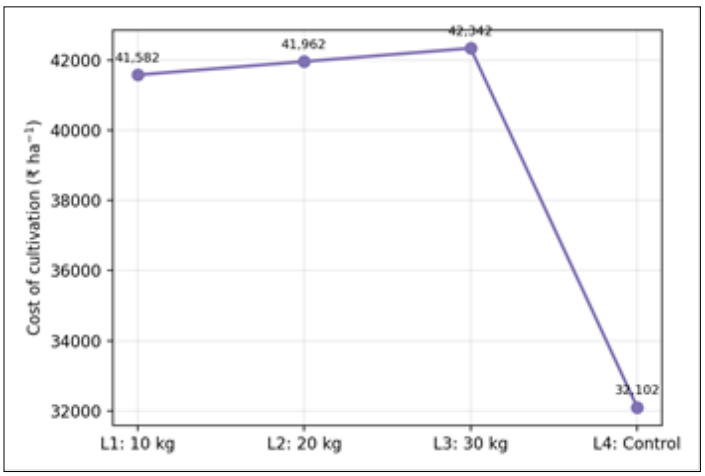


Fig 4: Cost of cultivation of maize as influenced by sulphur levels

6. Gross returns, net returns and benefit:cost ratio

Gross returns, net returns and benefit:cost ratio were all significantly higher under S_2 than S_1, with S_3 intermediate: gross returns of ₹ 1,44,725 ha $^{-1}$, net returns of ₹ 1,05,048 ha $^{-1}$ and a benefit:cost ratio of 2.60 under S_2, against ₹ 1,23,575 ha $^{-1}$, ₹ 84,588 ha $^{-1}$ and 2.14 under S_1 (Table 5, Fig. 5). Among levels, all three measures peaked at L_3 (₹ 1,57,667 ha $^{-1}$ gross returns, ₹ 1,15,325 ha $^{-1}$ net returns and a benefit:cost ratio of 2.72), significantly ahead of the control L4 (₹ 88,067 ha $^{-1}$, ₹ 55,965 ha $^{-1}$ and 1.74) (Fig. 6). The source × level interaction was non-significant for all three, with S_2L_3 giving the numerically highest gross returns (₹ 1,70,000 ha $^{-1}$), net returns (₹ 1,27,298 ha $^{-1}$) and benefit:cost ratio (3.98), and S_1L_4 the lowest (₹ 83,500 ha $^{-1}$, ₹ 51,398 ha $^{-1}$ and 2.60, respectively).

The superior profitability of bentonite sulphur and 30 kg S ha $^{-1}$ stemmed from their consistently higher grain and stalk yields, which more than compensated for the additional cost of the sulphur fertiliser and its application. These findings are consistent with the higher gross and net returns and benefit:cost ratios reported with sulphur fertilisation in maize by Maurya *et al*. (2005), Sutar *et al*. (2018) [8, 19], Bharathi and Poongothai (2008b), Padma *et al*. (2018) [11] and Choudhary *et al*. (2013) [4], and with the closely comparable economic advantage of bentonite sulphur over gypsum reported by Sutar (2012) [18] in a parallel field study on maize grown under similar *Vertisol* conditions and by Meena and Meena (2015) [9] in mustard on Rajasthan *Vertisols*, and with the significant maize-yield and profitability advantage of the same three sulphur sources recorded by Siddique (2007) and Varavipour (1993) [17, 20] in their respective thesis investigations.

Table 5: Cost of cultivation, gross returns, net returns and benefit:cost ratio of maize as influenced by sulphur sources and levels

Treatment	Cost of cultivation (₹ ha $^{-1}$)	Gross returns (₹ ha $^{-1}$)	Net returns (₹ ha $^{-1}$)	B:C ratio
S_1: Gypsum	36737	123575	84588	2.14
S_2: Bentonite sulphur	39677	144725	105048	2.60
S_3: Elemental sulphur	39827	134000	94173	2.33
S.Em±	–	1683.5	1450.9	0.03
CD @ 5%	–	6610.2	5697.0	0.09
L_1: 10 kg S ha $^{-1}$	41582	142333	100751	2.42
L_2: 20 kg S ha $^{-1}$	41962	148333	106371	2.53
L_3: 30 kg S ha $^{-1}$	42342	157667	115325	2.72
L_4: 0 kg S ha $^{-1}$ (Control)	32102	88067	55965	1.74
S.Em±	–	2657.5	2325.8	0.04
CD @ 5%	–	7895.7	6910.3	0.12
S × L interaction	–	NS	NS	NS
Highest (S_2L_3)	42702	170000	127298	3.98
Lowest (S_1L_4)	32102	83500	51398	2.60

Averaged cost of cultivation for S_1 to S_3 is the mean across L_1-L_4 for that source; the treatment-combination cost of cultivation ranged from ₹ 41,242 ha $^{-1}$ (S_1L_1) to ₹ 43,002 ha $^{-1}$ (S_3L_3) and is given in full in Table 6.

Table 6: Cost of cultivation (₹ ha $^{-1}$) of maize under each sulphur source × level combination

Combination	S_1: Gypsum	S_2: Bentonite S	S_3: Elemental S
L1: 10 kg S ha $^{-1}$	41242	41702	41802
L2: 20 kg S ha $^{-1}$	41282	42202	42402
L3: 30 kg S ha $^{-1}$	41322	42702	43002
L4: 0 kg S ha $^{-1}$ (Control)	32102	32102	32102

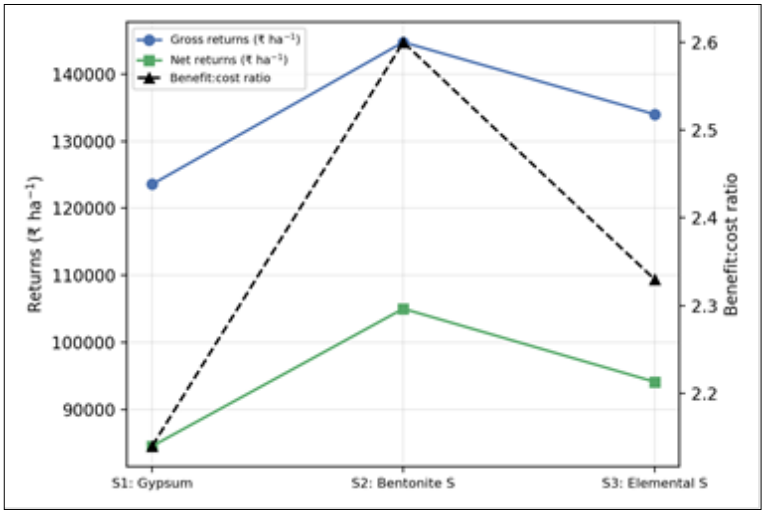


Fig 5: Gross returns, net returns and benefit:cost ratio of maize as influenced by sulphur sources

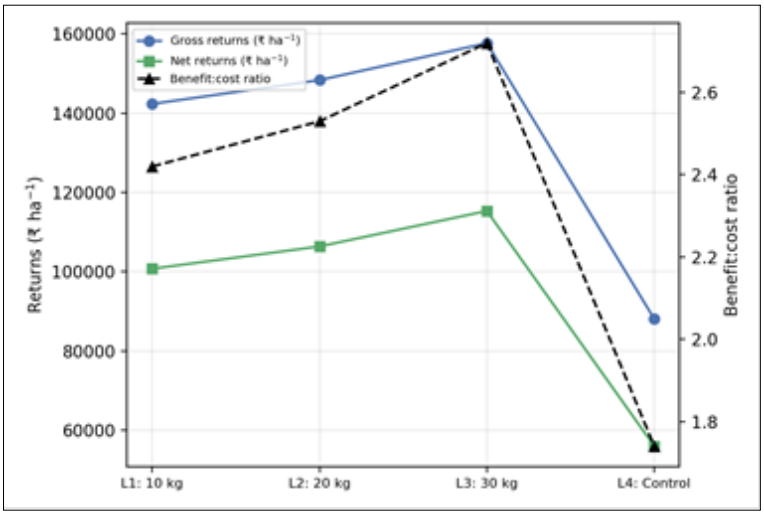


Fig 6: Gross returns, net returns and benefit:cost ratio of maize as influenced by sulphur levels

Conclusion

Nitrogen, phosphorus, potassium and sulphur uptake by maize, and the economic returns from its cultivation, were all significantly and consistently higher under bentonite sulphur than under gypsum, with elemental sulphur intermediate, and improved progressively with sulphur level up to 30 kg S ha $^{-1}$ in a sulphur-deficient calcareous *Vertisol*. The source × level interaction was non-significant for total nitrogen, phosphorus and sulphur uptake and for net returns and benefit:cost ratio, but significant for potassium uptake in straw and in total, indicating that the two factors mostly acted independently; even so, bentonite sulphur combined with 30 kg S ha $^{-1}$ (S_2L_3) gave the numerically highest value for every nutrient and every economic measure examined, and gypsum with no sulphur (S_1L_4) consistently the lowest. Given its higher nutrient uptake efficiency and the highest net returns and benefit:cost ratio recorded in this study (₹ 1,27,298 ha $^{-1}$ and 3.98, respectively), bentonite sulphur applied at 30 kg S ha $^{-1}$ is recommended as the most nutrient-efficient and economically remunerative sulphur management practice for maize cultivation on calcareous *Vertisols* of similar agro-climatic regions.

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